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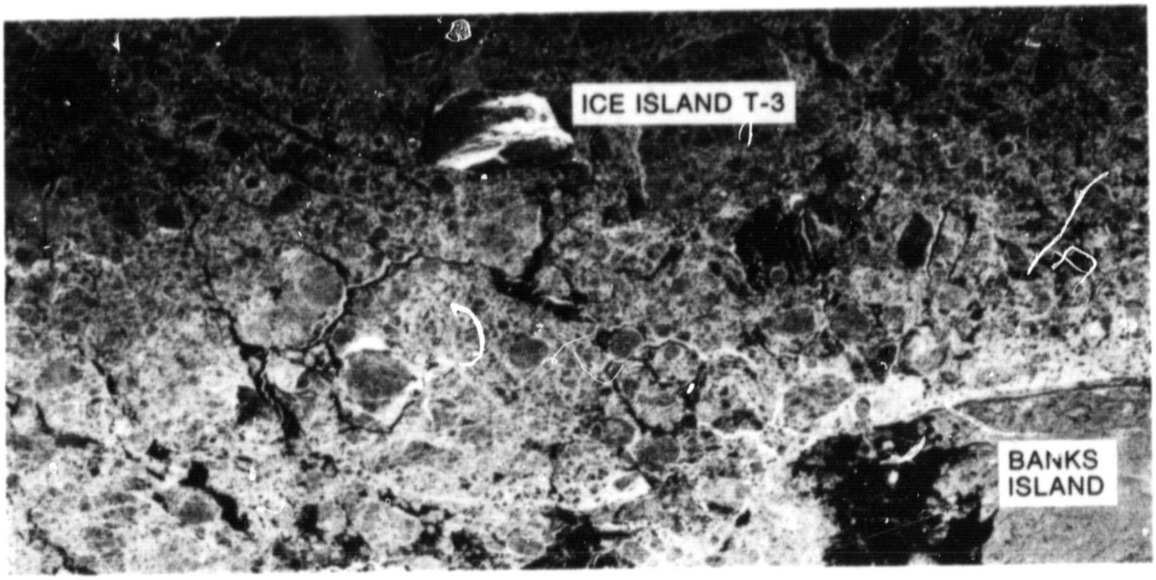

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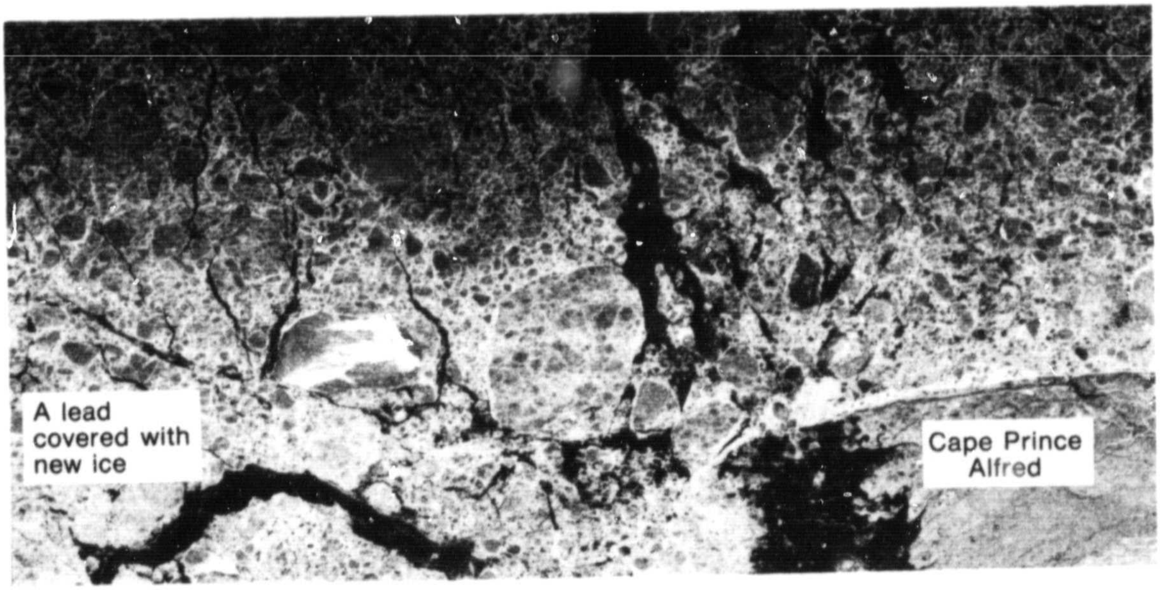

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These two images of sea ice in the Beaufort Sea were taken by Seasat with an L-band Synthetic Aperture Radar. They show the complex structure of the movement of the ice floes past Banks Island and the resultant open water areas (shown here covered with new ice). Ice Island T-3 is also clearly visible. The identification of features such as dark leads and light lacy ridges is useful to scientists and operating engineers who need to know ice conditions.

Sea-Ice Mission Requirements for the U.S. FIREX and Canada RADARSAT Programs

Report of the Bilateral Ice Study Team Workshop
Cornwall, Ontario
February 11-13, 1981

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ABSTRACT

The Seasat Synthetic Aperture Radar (SAR) data set has clearly proven the research and operational potential of such observational systems. As a consequence, the U.S. National Aeronautics and Space Administration and the Canadian Department of Energy, Mines and Resources have undertaken bilateral studies to define a future bilateral SAR satellite program. These studies have been given the names Free-Flying Imaging Radar Experiment (FIREX) in the U.S. and RADARSAT in Canada. The studies include addressing the requirements supporting a SAR mission posed by a number of disciplines including science and operations in sea-ice-covered waters. To define these requirements, a workshop held at Cornwall, Ontario during February 11-13, 1981 was charged with:

1) Identifying significant operational and research problems amenable to solution via the utilization of SAR data;

2) Defining the mission requirements (accuracy, resolution, spatial and temporal coverage, timeliness, etc.) that a prospective SAR satellite mission would have to satisfy in order to address the identification problems;

3) Recommending complementary data sets necessary to address the identified problems;

4) Formulating an experimental program to address questions which may arise during the course of the group's deliberations;

5) Defining a possible research program (prelaunch and postlaunch) that would be supportive of a future SAR satellite program; and

6) Outlining an approach for a limited operational demonstration of a SAR satellite system.

This report is the condensed written result of that workshop. It covers sea-ice research problems on which SAR would enable real progress, the ice information and total mission requirements, the mission components, the radar engineering parameters, and an approach to the transition of spacecraft SAR from a research to an operational tool.

FOREWORD

This document is one of a series describing the Free-Flying Imaging Radar Experiment (FIREX) mission requirements:

Science Requirements for Free-Flying Imaging Radar Experiment for Sea Ice, Renewable Resources, Nonrenewable Resources, and Oceanography

Sea-Ice Mission Requirements for the U.S. FIREX and Canada RADARSAT Programs

Nonrenewable Resources Mission Requirements for the Free-Flying Imaging Radar Experiment (FIREX)

Renewable Resources Mission Requirements for the Free-Flying Imaging Radar Experiment (FIREX)

WORKSHOP PARTICIPATION

BILATERAL ICE STUDY TEAM WORKSHOP

February, 1981
Cornwall, Ontario

Co-Chairmen: Dr. W. F. Weeks (USA), CRREL
Dr. R. O. Ramseier (Canada), AES

Ice Features and Measurement Parameters Committee

Chairman: Dr. D. Goodenough, Canada Centre for Remote Sensing
Dr. W. L. Jones, Langley Research Center

Mr. D. Lapp, AES
Dr. C. Livingstone, Canada Centre for Remote Sensing
Dr. R. Lowry, Intera Environmental Consultants
Dr. R. G. Onstott, Kansas University
Dr. S. Peteherch, AES
Mr. R. Schuchman, ERIM
Dr. S. Waterman, MacDonald - Detweiler Associates

Ice Dynamics and Thermodynamics Committee

Chairman: Dr. F. D. Carsey, GSFC (now JPL)

Dr. W. J. Campbell, USGS
Dr. W. Denner, Memorial University
Dr. V. Nerella, AES
Dr. A. Thorndike, University of Washington

Ice Engineering Committee

Chairman: Dr. J. Kreider, Shell Development

Dr. F. Bercha, F. G. Bercha and Associates
Dr. J. Rossiter, Huntec Ltd.

Ice Operations Committee

Chairman: Mr. T. Mullane, AES

Mr. H. Cheung, Arctic Pilot Project
Mr. G. Comfort, Arctec Canada Ltd.
Mr. M. Dunne, Leigh Instruments
Dr. D. C. Echert, Oceanographic Services
Dr. B. Mercer, Dome Petroleum Ltd.
Mr. J. Miller, Petrocanada
Mr. L. G. Spedding, Esso Resources
Captain P. Whitehead, Canadian Coast Guard

Ice Shelves and Icebergs Committee

Chairman: Dr. David Thompson, JPL
Mr. E. Sadler, DND

Observers:

Dr. D. Butler, NASA
Dr. R. Chase, NASA
Dr. C. Elachi, JPL
Mr. E. Langham, NHRI
Mr. C. Luther, ONR
Dr. L. McGoldrick, NASA
Mr. B. Warren, DOC (Canada)

Support:

Ms. K. Laidlaw, AES (at Cornwall)
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EXECUTIVE SUMMARY

MISSION REQUIREMENTS

The Seasat data set established the potential of Synthetic Aperture Radar (SAR) data for application to research problems in sea-ice science and operations. The basic utility of SAR is in locating, identifying, and tracking ice features of importance in a wide variety of scientific and engineering problems. Subsequent analysis has shown that an even more powerful sea-ice surveillance tool would result from supplementing SAR with an areal-integral measurement technique such as scatterometry, microwave radiometry, or both, and combining these data with meteorological and oceanographic data collected by satellite-monitored buoys. Clearly, a highly productive sea-ice science research mission can be defined for a satellite so instrumented, provided that a suitably designed research program commences prior to launch. In order to design such a mission, Canadian RADARSAT and NASA FIREX (Free-Flying Imaging Radar Experiment) study teams were set up to examine the research problems such a bilaterally supported mission could address, and to determine the mission requirements indicated to assure good progress on those problems. This document discusses some significant research problems associated with ice-covered seas, the consequent mission requirements, and the recommended satellite instrumentation.

Research questions requiring SAR information are divided into two broad classifications: science problems and operational problems, with much overlap and interrelationship. Science problems can be divided into (1) circulation of ocean and atmosphere, (2) climatology, and (3) the response of sea ice as a material. Operational problems can be divided into (1) fixed-installation design, (2) navigation, and (3) offshore activities. Simulation of operational application of SAR is recommended as a necessary step in the transition of SAR from a finely focused research tool to an operational tool; here the similarities to the Landsat program are obvious. Progress on the operational and science research problems requires SAR and ancillary satellite data, buoy data, improved knowledge of microwave properties of sea ice, and prelaunch pilot studies using Seasat, aircraft, or Shuttle data. An efficient means of production and an effective means of communicating the results to remote sites are also needed. All research and simulation activities call for an image-format presentation of a variety of ice types and features; however, some differences exist among activities as to required resolution and repetition or coverage. All activities either require or would profit by buoy data products, including measurements of the geostrophic wind vector and air temperature. Table 1 (page 2-14) summarizes the operational and science information requirements.

The program required consists of (1) the instrumented satellite with attendant ground and data-processing systems, (2) an information dissemination system capable of relays to remote points, (3) a data buoy monitoring system, (4) data supplementation and verification by aircraft, ship, and fixed

platforms, (5) more information on sea-ice microwave properties, (6) advances in image-processing technology to speed the quantitative analysis of the data, (7) simulation of operational use of SAR, and (8) sea-ice scientific research.

The satellite called for has, in addition to a buoy monitoring system and the required flight and data-link electronics, instrumentation in the form of the SAR complemented by a scatterometer and/or a radiometer. In general, the SAR is an identification and location tool for a number of ice features such as ridges, floes, and leads resulting in a data set from which ice motion and deformation data can be extracted. The low-resolution scatterometer/radiometer systems, on the other hand, measure distributed phenomena such as ice-type fraction or amount of open water. The scatterometer/radiometer data will therefore constitute a global ice extent and type data set. It will also have time and space scales suitable to weather and climate research and to operational forecasting applications in which local SAR data are used with a variety of other types of basin-wide low-resolution data. Also, the combination of a feature identification tool (such as SAR) with a well-calibrated, areally integrating tool (such as the scatterometer) will permit more quantitative estimates of feature variables. All of these instruments have flown in space aboard Seasat, and considerations are now underway by several nations for future flights of similar instruments.

If a SAR system were deployed in the absence of these complementary instruments, the optimum radar frequency for discriminating between first-year ice, multiyear ice, and water on radar backscatter alone would be between 11 and 15 GHz for incidence angles between 20 and 50 degrees. At frequencies in the range between 1 and 10 GHz, the differences in radar backscatter between different ice types are less significant. However, if the SAR system used for feature tracking is supplemented by a 19- or 37-GHz radiometer or a 11- to 15-GHz scatterometer used for ice-type determination, the recommended SAR wavelength would be at L-band (1-2 GHz) with like polarization. At the L-band frequency, first-year ice which has not undergone much deformation can easily be distinguished from multiyear ice, and highly deformed first-year ice and multiyear ice can usually be distinguished by shape and, possibly, by geographical location. While the trend for improved ice feature recognition in SAR data at higher frequencies is reasonably well established, the greatest changes for program success call for the use of systems which are proven in space, of known calibration, and produce familiar data. These systems are the L-band SAR and the higher frequency scatterometer or radiometer.

Other radar parameters can be approximately determined from summary mission requirements. The depression angle should be in the range $20^\circ < \alpha < 50^\circ$. A resolution of 25 m appears adequate although some measurements would tolerate a reduction to 100 m. The swath width required to obtain adequate coverage needs should be 200 km to satisfy operational requirements and somewhat less for many scientific programs. The orbit geometry should provide maximum areal coverage for the supplemental sensors as well as maximum orbit tracks over coastal waters in order for the radar imager to support the operational research objectives. Thus, an orbit providing SAR ground coverage poleward to 76° N in the form of long, nearly east-to-west transects across the Arctic, and scatterometer/radiometer coverage to approximately 85° N for science and for forecasting, is called for. If other satellites are deployed

which take the complementary data, the orbit could be lowered a bit. Should a more polar orbit be chosen to accommodate other measurements, the 200-km swath would become a minimum.

The data-processing requirement for operational research problems calls for daily processing of 30 minutes of data within 2 hours of aquisition. The scientific program would require processed data at that speed only rarely--1 or 2 minutes on 10 to 20 days per year--to support field efforts in areas where rapid changes in ice conditions are common (for example, the open ocean margin and the shear zone). For the remainder of the science program, data turnaround time is not appreciably a problem. Geographically, science data demand over a year will call for an uneven mix of zones of long-term surveillance and zones of brief, intense observation to document specific seasonal changes or to support field programs. Under most circumstances, data products would not be in demand sooner than a month after acquisition. However, the data required would need to be of optimum dynamic range and calibration. Thus, the operational research need would call for some 3×10^6 km^2 images per day with a 4-bit range and ± 2-dB absolute calibration, while the science program would require about half as much data processed on a relaxed schedule, possibly involving use of processor time in the summer, but calling for a 5-bit range and ± 1-dB absolute calibration.

As mentioned, the sea-ice science problems which would materially benefit from an augmented SAR deployment are divided into three categories: oceanic and atmospheric circulation, climatology, and materials response. The circulation of the ocean and atmosphere are affected by sea ice because ice changes the surface albedo, alters the fluxes of heat, mass and momentum between the water and the air, advects latent heat equatorward, changes the stability of the upper ocean, and influences the surface stress on the water column. Specific science questions on which significant progress could be made using data from this program include: How do surface fluxes modify the oceanic circulation of ice-covered seas? How do horizontal and vertical fluxes near the ice edge affect the edge location? What is the net heat loss of the Southern Ocean? What processes control the response of the ice pack to forcing at the coastal boundary? The key measurements of sea ice required for answering these questions are concentration, thickness, velocity, and pressure ridge density. Of these, SAR does an excellent job with velocity, a good job with concentration and ridge density, and provides some information on ice thickness via the determination of ice type.

The research problems associated with future operations in sea-ice-laden waters are divided into three categories: design of fixed installation, navigation, and offshore activities. Ice is of operational interest because it can damage both fixed or floating structures, it strongly influences surface transport even by icebreaker, and it can impede or occasionally enhance a wide variety of offshore support activities. Ice velocity, type, concentration, and ridge density are key measurements for operational problems just as they are for the science problems. Specific research questions from anticipated polar operations include: What is required to forecast the location of navigational hazards and of areas of ice not under compression? How can ridge parameters such as height be accurately determined? What kinds of ice features can be expected in a given season at a given location? What

is the impact of ice cover information on global weather forecasting? Also, as precise forecasting of ice conditions is important in polar operations, there is a particular need to improve the accuracy of short-term, 1-5 day, ice response forecasts.

In general, researchers involved with operational problems need accuracy in different areas than do researchers involved with science. For example, the computation of fluxes between the ocean and the atmosphere requires rather detailed knowledge of the ice thickness distribution with an emphasis on the accurate measurement of the areal fractions of thinner ice and open water. The operations problem, on the other hand, is primarily concerned with the exact location of thin ice, open water, and heavy ridging. Thus, the calibration needs are different; clearly more of the total operational problem can be more fully accomplished by a simpler, longer wavelength, Seasat-type radar. Such a system, complemented by a wide-swath coarse footprint instrument, such as a scatterometer or radiometer, constitutes the basic requirement for research on sea-ice operational problems. In the context of a spacecraft SAR development program spanning several decades, a simple SAR similar to the Seasat instrument would satisfy short-term operational needs and would also contribute significantly to progress in long-term science goals. However, it appears that these goals would be better met, of course, by shorter wavelength, higher-resolution systems of the future.

The proposed sea-ice imaging radar program can be summarized as follows. At the soonest possible time a satellite carrying a Seasat-type Synthetic Aperture Radar (SAR) should be deployed. The SAR system should be augmented by a system or systems that provide areal measurements of ice characteristics, such as a scatterometer or radiometer. Also a data-buoy interrogation system should be deployed. Such a combined system would largely satisfy the research community involved with operational problems and would also enable considerable progress to be made in those areas of sea-ice science concerned with ice dynamics. By the time improvements in SAR technology permit higher frequencies and higher resolutions, the science community should be prepared to exploit these new systems. At the same time the research community concerned with sea-ice operations problems should be prepared to justify an operational level SAR free-flyer. Thus, part of the recommended program for current consideration is concerned with the implementation of operational-simulation projects involving engineers, scientists, and managers from a variety of agencies and private organizations. These projects would be concerned with actual application exercises such as navigation of an ice-breaking tanker or deployment of a drill ship. This program, centered on flight of a Seasat-type SAR with supplementary instruments, would provide a valuable scientific data set plus operational experience that could be followed by more sophisticated flight systems with improved capabilities for both science and operations. Such developments would presumably be entirely supported by operational agencies and/or the private sector that is concerned with sea-ice operations. This overall program provides a logical exploitation of techniques for observing sea ice from space for the immediate and longer range future.

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I. MISSION INTRODUCTION

Seasat, the first dedicated oceanographic satellite, carried a unique instrument aggregation that produced a microwave data set which excited the geophysics community with its research potential. A striking element of this is the Synthetic Aperture Radar (SAR) data taken over the sea ice of the Arctic during the late summer/early fall of 1978. Although this data set has not as yet been thoroughly analyzed, the success achieved in preliminary analysis is more than sufficient to trigger serious support for the flight of another spacecraft SAR for systematic sea-ice observation. Investigations utilizing this proposed SAR system could result in significant progress in sea-ice research focused on problems of routine operations in ice-covered seas and on problems of a scientific nature concerning the role of the ice cover in the environment. The purpose of this document is to discuss such research problems, to point out the application of SAR data in developing rational approaches to their solution, and to determine the requirements supporting a SAR mission as established by these approaches.

Other related documents are available that discuss mission requirements in support of a SAR program for problems in the three additional areas of oceanography, renewable resources, and nonrenewable resources. This material was developed by a bilateral meeting on the Canadian RADARSAT and NASA Free-Flying Imaging Radar Experiment (FIREX) Ice Study Teams at Cornwall, Ontario on February 11-13, 1981. These committees were charged to:

1) Identify significant operational and research problems amenable to solution via the utilization of SAR data;

2) Define the mission requirements (accuracy, resolution, spatial and temporal coverage, timeliness, etc.) that a prospective SAR satellite mission would have to satisfy in order to address the identified problems;

3) Recommend complementary data sets necessary to address the identified problems;

4) Formulate an experimental program to address questions which may arise during the course of the group's deliberations;

5) Define a possible research program (prelaunch and postlaunch) that would be supportive of a future SAR satellite program; and

6) Outline an approach for a limited operational demonstration of a SAR satellite system.

The basic elements of the mission under consideration are the deployment of a spacecraft carrying both a SAR and complementary instruments plus a data-processing system to produce an engineering data set of backscatter images from the SAR as well as calibrated data sets from the complementary instruments, an interpretation scheme which converts these engineering numbers into sea-ice information, research programs for improving the interpretation

scheme and for using SAR data in geophysical research, and an operational simulation project. The objectives of the sea-ice part of the program are to simulate the operational applications of spacecraft SAR and to generate progress on science and operational problems in the sea-ice-covered oceans of the world.

The fundamental requirement of the SAR is to support research tasks by providing image data of sea-ice microwave properties which can be transformed into image-format data on ice type, movement, and deformation. This image data is applied to an extensive assortment of science, engineering, and operational problems. In general, identification of ice type can be accomplished in several different ways with different combinations of microwave radar, scatterometer, and radiometer data. Since several of these different mixes will equally enable resolution of ice type, a conflict in radar specification among the four basic mission requirement committees can be resolved without loss of data usefulness to the sea-ice community. Thus, an instrument aggregate to satisfy the sea-ice mission requirements can be derived to accommodate a wide variety of radar parameter configurations required by other disciplines.

II. RESEARCH PROBLEMS

Sea ice covers about 13 percent of the world ocean and it strongly affects the circulation of the sea and the atmosphere. Also, sea ice increasingly interferes with routine operational activities of commercial and industrial importance. As a consequence, a number of research issues in science and engineering have recently come into focus. Progress in sea-ice research depends on observations of ice conditions and weather for the polar oceans and seas of the world. The remoteness of the area under observation, the difficulty and hazard imposed by a harsh regional climate, and the required time- and space-scales of observation call for the use of space platforms and instrumented buoys as prime sources of data.

The basic information sought in support of research tasks in sea ice is the answer to certain basic questions: What is the instantaneous conformation of the ice pack? How is it changing? The scientist may wish to know the meteorology, the surface roughnesses, the thickness, and the fraction of open water in the pack in order to estimate heat and momentum fluxes. Similarly, the structural designer needs to know the compactness, the frequency of occurrence of specific hazards, and the velocity of the ice. In fact, the lists of needed information for scientific and applied problems are almost identical even though the pathways for the application of the data, once acquired, may be quite different. There are, of course, some differences. Those who work on operational problems on ice-covered seas usually have geographically limited domains of interest. Scientists, on the other hand, are usually interested in developing general methods for describing the behavior of sea ice and, in principle, these methods should be equally applicable at all sites. Similarly, the engineer is often interested in the exceptional, rare event, a peak value occurring on the "tail" of the distribution, while the scientist usually is more concerned with mean values. Still, as will be shown, all investigators have surprisingly similar measurement requirements giving rise to the recommendation of a common observational system.

The science problems in which SAR data can play a role are primarily associated with the modification of surface fluxes due to the presence of sea ice. In the central pack-ice areas of both polar regions, the ice cover influences the oceanic circulation by modifying the surface stress and by producing thermohaline transport, especially at coastal margins. At the pack-ice margin, the ice cover influences atmospheric circulation through albedo changes and latent heat export. These issues indicate the central science problems on which SAR data can materially contribute to progress: "What is the circulation of the water of the major ice-covered seas?" "What is the role of the fluxes at the ice margin in atmospheric circulation?"

Sea ice is also a component of the global climate system, and descriptions of the ice cover and of some of its related long-term average fluxes are important climatological variables. Such information is principally useful in comparing the present state of the cryosphere with the state associated with previous climates as well as with the state forecast by various predictive schemes such as that of Manabe and Stouffer (1980)

concerning the response of the climate to increases in atmospheric CO_2. Finally, sea ice responds mechanically in a complex way to stresses from the ocean and the atmosphere. The rheological processes associated with this response are interesting and important in their own right, and understanding these processes is critical to a proper calculation of ice conditions and thus of stresses and fluxes in the polar oceans and to the development of a sound methodology for forecasting a variety of engineering quantities.

Operational research problems concerning sea ice are usually concerned with describing the exact nature and location of an ice hazard as well as predicting its formation, movement, and ultimate deterioration. For example, navigation through ice-laden water by vessels, such as ice-breaking tankers, requires information on the location and orientation of leads and thin ice areas. At the same time, the ship captains need to know the precise location of regions of heavy ice and ridges which can impede or even cripple the vessel. Similar concerns are shared by operators of stationary drill ships, by harbor masters, and by designers of both near-shore and deep-water fixed facilities. Thus, the principal research problem in most applications in sea ice is to develop an observational capability to locate and identify such ice features and hazards and to develop models to predict their occurrence and movement.

A. SEA-ICE SCIENCE PROBLEMS

1. Introduction: Ice Dynamics and Thermodynamics

A number of sea-ice science problems are such that significant progress can be expected from using data from a properly designed satellite-borne remote sensing program structured around a SAR system. The information of greatest significance is the specification of the drift and deformation of the ice pack on a number of scales. Also important is the identification of differences in ice character such as the distinction between first-year and multiyear ice in the Arctic and the estimation of open water area.

For efficiency of discussion, sea-ice science problems will be divided into three broad categories: circulation, climatology, and materials response. As might be expected, there is considerable overlap in these problems. Some specific science problems in each category are:

(1) Circulation

What is the oceanic circulation in ice-covered seas?

What is the role of sea ice in atmospheric circulation?

How do the fluxes of the marginal ice zone influence the location of the ice edge?

What is required for improved short-term forecasting of ice conditions?

(2) Climatology

What is the mass balance of sea ice?

What is the heat balance of the Southern Ocean?

(3) Materials Response

What is the role of pack-ice fabric in ice dynamics?

What processes control the response of the ice pack to forcing at the coastline?

All of these problems are interwoven. In fact, in some cases it may not be possible to answer one question in the absence of progress on two or three other questions. For instance, in the case of mass balance and oceanic circulation, estimations are needed of quantities obtained in answering all the other questions. In addition, the science problems bear directly on the operations problems, the primary differences being that the engineer wishes to know what to expect and when and where it will occur while the scientist wishes to know why certain processes are taking place and what significance they have.

In the discussion of research issues which follows, the research question is first discussed. Then information needed to describe the processes at work is listed, the specific mission of the SAR satellite is indicated, and the overall research program needs and time tables are discussed.

2. Circulation

(a) <u>What is the circulation of the ice-covered oceans?</u> In ice-covered oceans the stress at the water surface and the density profiles in the upper ocean are strongly affected by the presence and formation of sea ice. Carmack (1981, private communication) has sketched a conceptual model of the circulation of the Arctic Ocean (Figure 1) and others have examined and modeled it (Aagaard, 1979; Semtner, 1976). While this picture is intentionally vastly oversimplified, it displays many important aspects of the problem: communication with the North Atlantic, clockwise surface stress in the basin, and thermohaline and shelf processes at the boundaries. Assuming the processes of the model to be the processes actually at work in the ocean, there is a need to quantitatively describe each component in order to model the whole. In the context of this program, the role of ice movement and formation is clear, but the consequences and strength of the air-sea-ice interactions are largely unknown. In the northern hemisphere, the most notable water mass modification occurs as warm Atlantic water moves into the Arctic basin through the Eastern Fram Strait and the Barents Sea and cold water retreats equatorward through the Western Fram Strait and the Canadian Archipelago. Additionally, the cold and rather fresh Labrador current moves equatorward to interact with and flow below the Gulf Stream. In the Southern Ocean, the ice acts as a salt engine producing cold, high-salinity Antarctic Bottom Water and, possibly, maintaining the salinity difference between the Atlantic and Pacific Oceans. Thus, it is useful to inquire how latent head

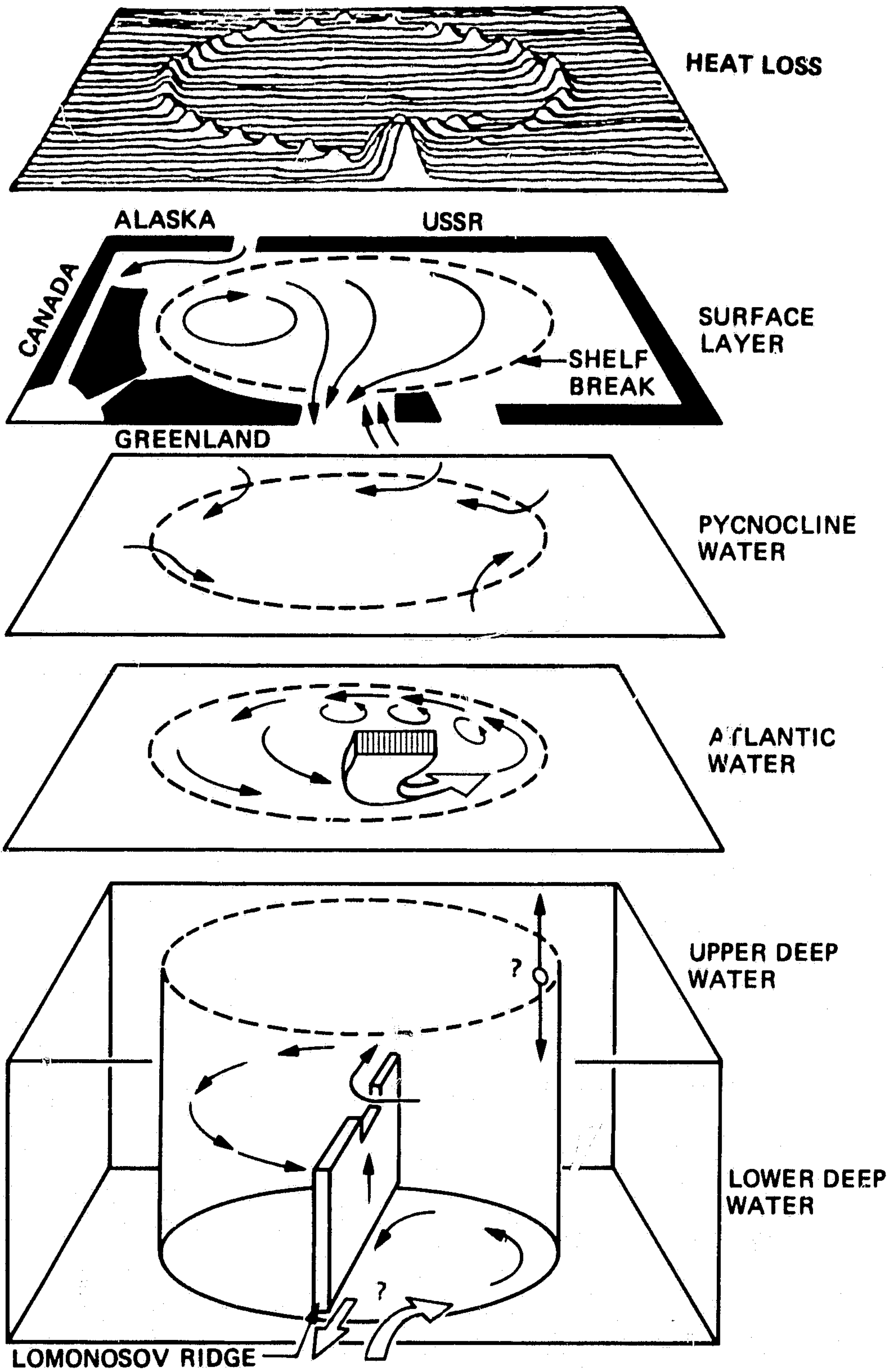

Figure 1. Schematic circulation of the Arctic Ocean (Carmack (1981), private communication). Fluxes of heat and momentum at the surface strongly affect flow in the Atlantic water and above, the water masses which communicate most with the world ocean.

advection, insulation, and salt rejection by the ice cover influence basin scale circulation.

Information Required. The influence of ice cover on circulation primarily results from changes in the stress at the ice-ocean boundary and in the modification of the density structure of the water column through cooling and salinity changes. Such density modification can affect the surface mixed layer itself in the summer when nearly fresh ice melts, reducing the salinity, and in the winter when brine rejected from forming ice remains in the mixed layer while the salt-deficient ice is removed by wind. This density modification can extend to deeper layers if convective plumes sink below the pychnocline to increase the density at such deeper layers or when wind-driven mixing occurs. Thus, the information required to quantify circulation effects is the density and velocity of the ice-covered water and the dynamic and thermodynamic consequences of the surface fluxes. The requisite information is the heat, momentum, ice, and mass budgets, and the initial temperature and salinity profiles of the water column. These variables are essentially the local circulation and mass balance derived from dynamic-thermodynamic calculations.

Mission. The role of the radar satellite in oceanic circulation research is in measuring the ice deformation, removal, and formation--and thus the ridge and open water production as well as the production of new ice in leads and polynyas. Ice growth must be estimated using environmental data on air temperature, wind speed, cloud cover, water temperature, and surface albedo. This information must come either from <u>in situ</u> platforms such as buoys or from regional meteorological analyses or climatological means.

Program. A program for assessing the role of ice in ocean circulation relies on modeling the basin-wide circulation and on accurate mass balance and thermodynamic modeling. These are not established calculations, but in fact are commonly listed as science problems for the polar regions. Progress on this project calls for circulation research as well as studies of the seasonal mass balance, which itself requires SAR data. However, circulation and water mass modification for specific regions of the ocean are poorly understood phenomena, and work should begin to simulate the effects of ice processes on water column density changes so that specific ice cover details can be parameterized. Thus, this research program should begin as a series of modeling and sensitivity analysis studies well before SAR launch.

(b) <u>What is the role of sea ice in atmospheric circulation</u>? Air masses moving over the snow-covered, sea-ice-laden ocean experience cooling both aloft and at the surface with the establishment of a cold stable lower layer. Sites such as leads and polynyas where open water and thin ice occur produce upward heat and moisture fluxes. Thus, air-ice interaction depends strongly on air and ice temperatures and on the relative areas of open water and thin ice. The ice margin, a site of sharp concentration change, is a region of particularly strong air-sea-ice interaction.

Information Required. Research in atmospheric circulation principally involves the examination via a variety of simulations of the sensitivity of global circulation to changes in initial and boundary

conditions. Therefore, a key requirement for studying the role of ice in atmospheric circulation is a Global Circulation Model (GCM) that is properly responsive at high latitudes. This atmospheric model must have as input an appropriate ice surface temperature such as could be developed from ice concentration, and ice drift velocity data taken by SAR and ice thickness from modeling. It is also essential to know the surface albedo calling for information on snow cover, ice concentration, and ice type. The effect of ocean cooling by ice melt at the margin may also be significant; if so, ice thickness is also needed at these locations.

Mission. The role of RADARSAT in atmospheric circulation research is in providing ice type, concentration, drift speed, and local meteorological variables. Clearly also of considerable importance is the sensitivity of the GCM that is utilized in the study.

Program. Research in the response of the atmospheric circulation to various changes in the sea-ice cover is not new. Indeed, much is known on both the synoptic and global scales. At present, however, models are not adequate for a proper analysis of this problem, as high-latitude atmospheric divergences are poorly simulated. Needed are better models which could be developed by the satellite launch. These models should be driven by simulated data to determine sensitivity and subsequently by actual data to study effects on circulation and forecasting skill.

(c) <u>How do the fluxes of the marginal ice zone influence the location of the ice edge</u>? The marginal ice zone (MIZ) is an area of growing scientific concern and interest. There are many scientific and engineering problems associated with the energy and mass balance of the MIZ, but probably the most critical one concerns understanding the horizontal and vertical fluxes and how they control the ice edge location. It is extremely difficult to carry out <u>in situ</u> observations of the ice edge as both manned and unmanned stations have only poor chances for success. Remote sensing techniques such as SAR can definitely help in providing answers to many of the questions concerning the energy and mass balance in this region. There are several different types of MIZ: some that are dominated by advection along a coastline--e.g., the Labrador region, some that are dominated by thermodynamics--e.g., northeast of Svalbard and the Bering Sea, and some that are complex mixtures. Presumably studies will have to be carried out in several different regions to study such variations.

Information Required. The extent of the MIZ is not precisely known; in fact, the distance into the pack and into the open ocean over which processes are affected by the presence of the ice boundary is probably highly variable with place, weather and season. The penetration of ocean swell into the ice is clearly an important deformational process, thus, it is important to measure the penetration distance and the corresponding effects. The meteorology and basic oceanography of the margin region must be known. The ice velocity and thickness well upstream from the margin are a measure of the total latent heat flux of the marginal domain. Finally, the mechanical and thermodynamic processes within the margin--the breakup, rafting, and finally the melting of the floes--must be observed and documented in considerable detail.

Mission. The observational problems at the ice margin exist on several scales, the interfloe scale of tens of meters, the ice-edge scale with a typical length of a few hundred meters, the mechanical scale for waves and swells of about 100 km, and the air-sea mesoscale of about 200 km. These space scales impose time scales from about 1/4 day for the interfloe margin to perhaps 3 days for the air-sea mesoscale. The observation parameters vary in the different regions, giving rise to a complex mix of resolution needs if each event must be monitored. In many cases, however, the interfloe interaction may be parameterizable from a knowledge of the ice floe geometry and wave energy.

In order to contribute to estimating horizontal and vertical fluxes and to understanding the processes in the ice margin, high-resolution, high-repetition rate data are required. These must be provided initially by multisensor aircraft systems and subsequently by models. However, to obtain information about the larger scale events which drive and initiate interactions at the smaller spatial scales, measurements are called for which cannot be provided by aircraft, thus calling for a satellite. In the larger scales, resolutions must enable velocity descriptions which are similar to those which could be obtained by using Seasat data which had a resolution of 25 m.

For studies of the ice margin, it is important to develop the ability to extract from the satellite record information on minor ice types that do not occur in significant quantities in the central pack. It is also important to be able to recognize the signatures of ice types representative of the central pack which are now found in the warmer, wetter environment of the ice margin. This surface microwave properties work has barely begun. It will be badly needed.

Program. The satellite SAR should be coordinated with a marginal ice-zone field program. This would involve investigations on the ice, with support from ships, helicopters, and unmanned observing stations (buoys and moorings). These buoys, which will surely become routine ocean data sources, will measure winds, currents, waves, temperature/salinity sections, radiation balance, sea surface slope, and perhaps even some ice properties.

(d) What is required to provide short-term forecasts of ice conditions? The short-term, or about one week, forecast of ice conditions is principally an operations problem, but it is listed under science for a number of reasons. Most important, the dynamic response of ice to environmental driving occurs on a time scale of 1/2 day to 3 days, and this short-term response, reflecting ice acceleration and deformation critical in engineering problems, is basically a science problem--the processes are not understood. The forecast problem is to observe the extent, concentration, velocity, thickness, and ridging intensity of the ice at one time and to predict the values of those variables at a time, a few days in the future, using oceanographic data as required and meteorological forecasts. Clearly the quality of the meteorological forecast is critical.

Information Required. The forecast of ice parameters requires three types of information and an appropriate numerical model. The

information consists of ice conditions, ocean conditions, and the meteorological forecast for the period of interest. It may be that ocean conditions can be obtained satisfactorily from the climatological record. The meteorological forecast will be a problem and may require considerable subjective analysis. The ice information needed is extent, type, concentration, velocity, and ridging.

Mission. The data on ice conditions must be obtained from aircraft or spacecraft surveillance. The variables whose measurements are required (extent, type, concentration, velocity, and ridging) are readily obtained from space-borne SAR. Acquiring the same data from aircraft would be uneconomical on synoptic time and space scales. Oceanographic and meteorological data will probably require buoys with appropriate data links.

Program. Research programs to develop improved short-term ice forecasts are now underway at a variety of institutions. The research topics extend from ice rheology to studies of the atmospheric and oceanic boundary layers. Should satellite SAR data become available, work will be necessary to facilitate the integration of SAR-derived information into the models in the form of initial conditions and updates.

3. Sea Ice in Global Climatology

(a) What is the mass balance of sea ice? It is often surmised and demonstrated in various fashions (Manabe and Stouffer, 1980; Weller, 1980) that the global coverage of sea ice is a sensitive indicator of the global climate. While recent data on the ice coverage of the Arctic at its summer minimum show that the variations are not particularly large (Carsey, 1982), there is no reason to doubt that the ice and snow cover (or some index such as the ice expelled through Fram Strait) will respond sharply to changes in a global mean variable such as surface air temperature. The task of accurately measuring the mass balance requires seasonal knowledge of ice extent, concentration, and thickness of a spatial scale similar to characteristic scales used in current models of global circulation (roughly 100 km).

Information Required. The measurement of mass balance requires the tabulation of the local mean areal coverage of each ice species as well as its mean thickness. In the Arctic, a reasonable ice breakdown is open water, thin (<0.5 m) ice, first-year ice, multiyear ice, and heavily ridged ice. In certain cases it might be appropriate to add new ice (<0.1 m) and melting ice. These quantitites have been measured in small areas by intensive aircraft and submarine transects (Wadhams, 1981), but global estimates have not as yet been made. In the Southern Ocean not enough is known about the ice conditions to specify a reasonable list of categories of sea ice. A SAR satellite data set coupled with appropriate model calculations could provide a means for making such a list.

Mission. A space-borne effort at mass balance could accurately determine, if only on a sampling basis, the ice categories listed above. Passive microwave, visible light, and IR sensors are limited by weather, emissivity variations and other unknowns, although the passive microwave systems do an excellent job of coverage measurement which would improve the

accuracy of the intensive sampling provided by SAR. The SAR image does a good job of locating and identifying ridged ice but is probably incapable of further quantitative estimates of mass or volume. Thus, modeling is required to keep track of the production of ridges--usually from thin ice. This required modeling is not much advanced of modeling efforts that are now done routinely.

Program. A method for utilizing modeling methods and SAR data to estimate the global mass balance of sea ice is straightforward. A problem will be in the design of a sampling scheme for using data from a part of the ice cover to estimate coverage. Also, the laborious task of rapidly extracting data from even these areas should be reduced by improved image processing techniques. To estimate the conversion of thin ice into pressure ridges, models supported by SAR data should be verified in selected areas by laser profiles from aircraft. Such work will provide estimates of the areal extent of ridged ice and the thickness of this heavy ice.

(b) What is the heat balance of the Southern Ocean? The southern Ocean, i.e., the portions of the Pacific, Atlantic, and Indian Oceans south of the Antarctic Polar Front (about 55^{o} S), is where the majority of heat loss from the world ocean occurs. The heat is removed from the sea by convection, radiation, and evaporation, in declining order of importance. The total heat lost has been estimated by several techniques (Toole, 1980; Trenberth, 1979) with a variety of results. The total heat flux and the distribution of this loss through the water column is thought to change little interannually, but this has never been verified. One heat loss component is represented by the production of cold salty bottom water which makes up the primary abyssal layer of the world ocen. The relationship of this heat loss to world climate is significant over a large range of time scales from the annual cycle to the response time of the abyssal sea (on the order of 500 years).

Information Required. To estimate the heat budget of the Southern Ocean, a complete description of the heat content and mean flow trajectory for each water element is needed. This is, of course, impossible even in a sea which is not ice-covered, remote, or beset by interfering weather as is the case in the Southern Ocean. An alternative strategy is to define surfaces and measure fluxes across appropriate surfaces. Optimum surfaces for this problem appear to be the ocean/ice/snow upper surface and the nearly vertical polar front.

Estimates of the energy fluxes at the ice surface are straightforward, if not difficult. The required information is air temperature and humidity, wind speed, water surface temperature, ice concentration, ice thickness, snow cover, and cloud cover. Key parameters, such as the drag coefficients, must be approximated with resulting errors. Flux measurements across the Atlantic circumpolar front are more difficult, as the mechanisms are not well understood (Toole, 1980). Of course, the net heat loss of the ocean can still be evaluated as the loss through the upper surface, and this can be set equal to the meridional component, but the effects of individual processes are lost and the significance of the error in seasonal changes is increased.

Mission. The role of a radar satellite in the calculation of the heat flux of the Southern Ocean is in establishing the ice description terms--concentration, thickness, and equatorward (latent) heat flux. Ice concentration is computed for the Southern Ocean from the passive microwave sensors (Gloersen et al., 1978; Carsey, 1980), but it would be useful to verify these estimates by radar image analysis. Ice thickness must be computed using mean ice advection and ice deformation data obtainable only by radar satellite. The atmospheric terms which are required to compute actual fluxes are currently estimated by the Australian weather service and archived at NCAR. This body of data will inevitably increase in quality in the next few years. Water temperatures and trajectories remain a problem which must be attacked by modeling and buoy deployment.

Program. A program for using SAR data in a calculation such as this is fairly clear-cut. There are two basic tasks--verification of the ice concentration estimates and of the ice dynamics calculations. The verification task is straightforward and could be initiated by organizing a pilot study using data from either aircraft or spacecraft or combinations of both. The second task is more involved; a modeling effort such as that of Parkinson and Washington (1979) for the total Southern Ocean must be established. The model would differ from those in existence today in that it would utilize satellite-derived ice velocity fields as input data. A program to develop and test such a model should get underway at least three years before spacecraft launch.

4. Materials Response

(a) <u>How does the morphology of the ice pack affect its behavior?</u> The properties of sea ice on a geophysical scale are quite different from the properties of laboratory-sized specimens of sea ice. For example, its large scale properties are controlled by the size and shape of the individual ice floes which make up the ice pack, not by the bonding energy in the ice lattice. Theories of the behavior of the ice pack recognize this, of course, by incorporating mechanical constitutive laws that are quite different from the laws for ice itself. Changes in ice morphology also affect ice behavior by changing the nature of the surfaces exposed to the wind and ocean, the production of ice in leads, and the exchange of heat between the ocean and atmosphere. A satisfactory theory of pack-ice behavior should include parameters related to ice morphology as internal variables so that they both influence and are influenced by the ice behavior.

What are these ice morphology parameters and what is known about them? During most of the year, long jagged leads run through the ice pack. The geometric arrangement of the leads has never been adequately described, and it is not at all clear just what sort of description is appropriate. It is clear, though, that the approach should be to describe the leads rather than the ice floes. In fact, during the winter, individual floes are commonly not particularly well defined. It is exceptional to find the traditional floe--a flat piece of ice with a generally rounded outline that is completely surrounded by ridges and open leads. In the late summer, the reverse is true. The leads have lost their liner character and are all joined into a lacey

network of open water. At this time, however, the individual floes are easily distinguishable.

SAR data are well suited to observe such sea-ice morphology. On the basis of Seasat SAR imagery, we can be confident of distinguishing open water and very thin ice from thick ice. The Seasat imagery also contains useful information about the roughness of the upper surface of the ice.

Individual pieces of ice move as rigid bodies. Essentially, the deformation in the ice pack occurs at the boundaries between these ice pieces, and the velocity field is characterized by discontinuities between the rigid pieces of ice. Therefore, the sizes of the individual pieces affect the structure of the velocity field. When the dimensions of the pieces are comparable to the scales of the forcing, as they can be (based on a small sample of Seasat data) or comparable to the distance to the nearest coastline, the velocity field will be strongly affected. In any event, there are close connections between the geometry of the ice pack, the velocity field, and the local deformation processes, and these connections have been little studied.

SAR is the best available tool for detailed observations of the spatial structure of the ice velocity. Other techniques can give better time series observations at a few isolated points, but at the present only SAR can give good spatial and reasonably good temporal resolution.

Mission Requirements. It is too soon to give more than a general idea of the requirements for a successful measurement program. The spatial resolution must be fine enough to detect most of the active leads, and to determine the ice deformation. Targets with a reasonable radar contrast separated by roughly 25 m should be resolvable, and the relative geographical location of features should be accurate to about the same level. Sequential images of a desired Lagrangian test region 100 x 100 km or somewhat larger would be needed with the sampling occurring at intervals of 1 to 2 days over a period of about a month. This set of observations should then be repeated several times in each of several different regions. Several hundred deformation measurements on a grid scale of 100 x 100 m would probably suffice.

The procedure for making the ice velocity measurements involves determining the locations of features which can be identified in successive images separated by 1 or 2 days. Recognition of features in both images may come difficult as the feature azimuth changes. Absolute statictics on feature-tracking success have not been established; they probably cannot be without a free-flying SAR.

Complementary Data. This experiment is fairly independent of complementary data. One useful way to strengthen the SAR ice velocity data would be to install a few (3) data buoys at selected sites on the ice with good navigational capabilities and a radar cross section which would make them visible on the SAR image. The known positions of these buoys would serve to register the image irrespective of feature identification.

Preliminary Experiment Program. The proposed observation program is research oriented and should be kept as flexible as possible, so that knowledge gained from preliminary studies can still affect the final experiment design. The Seasat SAR data are a good data base for preliminary studies. Automated techniques for extracting displacement data from pairs of images are essential to the success of this program in other than a labor-intensive research mode. The best techniques for this may involve completely automated recognition of features by computer or the human recognition of features assisted by automated measuring and recording of the data.

The understanding of floe and lead geometry and surface roughness needs to be developed in parallel with the data collection. It is not clear just what geometric parameters could be most revealing or just how to most readily extract this from the SAR imagery. Candidate parameters are lead widths, total lead area, floe sizes, ratio of floe perimeter to area, and so on.

(b) <u>What processes control the response of the ice pack to forcing at the coastline?</u> The coastal ice margin is a region of complex and important processes. They are complex because the oceanic and meteorological driving terms are influenced by small-scale effects, the shallow water results in the grounding of the deeper keels, producing irregularly spaced land-fast impediments to ice flow, and the shear of the pack velocity is dominated by floe-floe interactions. The processes are significant because the cold saline water produced by ice formation is able to reach appreciable depths by flowing down the continental shelf to mix and/or continue to sink, the shear zone is a reliable source of open water and hence of ice production and of heat loss, and, finally, much human activity takes place above and in such shallow water areas.

Information Required. The predominant processes of the coastal regime can be usually described in broad general terms. However, a great deal of local information such as bathymetry, tides, currents, winds, and ice cover are invariably required for accurate simulations or estimates. Further, the ice well away from shore can exert a dominating influence which must be considered in many problems. In these cases, the ice of the shelf region must be very thoroughly described as to roughness, thickness, ridging, strength, and age. The bathymetry must also be well known, as is definitely not the case for many polar areas. The tides should also be known, although the tidal excursions of the Arctic Ocean itself are commonly quite small. Winds are also required, including observations of strong sea breezes. Finally, the rheology of the ice in this complex environment must be understood.

Mission. A radar observation program would provide a means of measuring ice velocities in coastal regions. This can be done very accurately using SAR imagery. Ridge-building processes of the shear zone can also be observed, and the rate of open water production can be specified for all seasons. The motion of ice floes in water deeper than a likely keel, for example 100 m, at locations several floe dimensions from the nearest grounding point, will not be strongly influenced by the shore, and it can be used as a driving parameter along the coast.

Program. The problem of ice-pack response at coastlines is currently under examination by several scientists and engineers. The objective of the program utilizing space observation should be to collaborate where possible with these activities in order to understand the observational situation, the overall needs, and the total system behavior.

5. Science Summary

The role of radar observations to enable progress in sea-ice science has been examined for problems in air and ocean circulation, polar climatology, and materials response. In each case, spacecraft SAR data on ice deformation, ice type, and ice velocity were needed on time scales that are usually meteorologically defined, 1 to 3 days, and space scales determined by ice floe interaction, less than 100 m. Data on global extent are usually considered to be acquired by the low-resolution sensors, which are proven devices in that area. Table 1 shows observational requirements for the SAR sea-ice science mission. In general, the problems are such that ice velocity derived from coarse-resolution data (<100 m) and limited coverage would fuel initial studies which would be expanded and made more accurate by subsequent higher resolution systems with broader, more frequent coverage. This approach would essentially describe the consequences of ice dynamics first, and, second, would examine the actual deformation events on a floe-by-floe basis using later technology. Similarly, calculated fluxes would be more accurately estimated by the subsequent systems.

B. OPERATIONAL PROBLEMS

1. Introduction: Ice Hazards and Features

There are a number of ice hazards and features that are of concern to the operational community. To be specific, the following are of obvious interest: the location and nature of the pack-ice edge, multiyear ice, very large pressure ridges, ice islands, icebergs, leads, and thin ice.

a. Problem Definition. The problem here is, in principle, rather simple. One needs to be able to unambiguously identify and describe each of the above entities. In some cases, it will only prove possible to identify features that are larger than some specific size. These "cut-off" sizes for each type of ice feature must be known rather precisely. Some objects such as icebergs may be "invisible" from certain look angles. The ice edge may be clearly revealed only if ice concentrations are greater than some specific value. In short, we need to know which hazards we can detect and which may go unobserved, so that we can consider utilizing other systems to observe them. In the next step leading to application, a census should be assembled that, for each type of hazard, gives the frequency versus hazard size. This data might come from a combination of SAR and the *in situ* or historical record. Next sequential SAR images should be utilized to study the movement of the hazards. Studies should also be completed that would facilitate the use of automatic image analysis techniques to speed data reduction. Finally, work should be performed to determine the optimum means

Table 1. Summary of Information Requirements (Operational/Science)

Variable	Resolution	Coverage	Registration	Timeliness	SAR	Other
Pack-ice edge	0.5/10 km	Daily/3 daily	0.5/10 km	Day/month	Yes	Scatterometer or radiometer
First-year ice	10%	Weekly	5/10 km	Day/month	Yes	Scatterometer or radiometer
Multiyear areal coverage	10%	Weekly	5/10 km	Day/month	Yes	Scatterometer or radiometer
Multiyear floe	20 m/NA	Weekly/NA	0.5 km/NA	3 days/NA	Yes/NA	None/NA
Large ridge height	50 m	Weekly	0.5 km	3 days	Doubtful	None
Ice islands	20 m/NA	Weekly/NA	2 km/NA	3 days/NA	Yes	None
Icebergs	20 m/NA	Weekly/NA	5 km/NA	3 days/NA	Probable	None
Leads/thin ice	30 m	Daily/3 daily	0.5/10 km	3 days/month	Yes	Scatterometer or radiometer
Surface temperature	100 km	3 daily	50 km	Day/month	No	Buoy
Geostrophic wind speed	1 m/s	Daily	100 km	Day/month	No	Buoy
Direction	20°	Daily	100 km	Day/month	No	Buoy

NA = not applicable.

a/b = a, operations; b, science requirement.

for incorporating updates of the geographic position of ice hazards and features into ice dynamics models for predictions of their future positions.

b. Information Requirements. Information is needed on the size and general characteristics of the different types of detectable ice hazards. Techniques for rapidly determining the exact positions of such objects on radar imagery are also needed. The sequential monitoring of regions that produce icebergs (for instance the Ellesmere Ice Shelf, the Erebus Glacier Tongue, the edge of the Ross Ice Shelf) is also useful. Table 2 gives a summary of the mission requirements for ice hazard research.

c. Experimental Program. For each of the five ice features and hazards, the backscatter data is incomplete; it should be collected at a variety of resolutions, look angles, frequencies (C, X, L), and polarizations. The resulting imagery should then be compared using high-resolution photogrammetric observations as a calibration. The SAR imagery should also be used to develop automatic image-processing procedures that give target identification, characteristics (particularly size), and position. Methods for rapidly incorporating these results into ice forecasting models should also be developed.

d. Application. The hazards and features discussed above relate to the major operational problems in ice-covered seas: fixed-structure design, navigation, and offshore activity. At the present time such problems are most strongly coupled to oil exploration and production from the continental shelf areas of the polar regions, but in the future they will undoubtedly apply to other resource development activities, fishing, and military activities. Finally, it is important to restate that the features and processes which are important to applications and engineering problems are the same as those important to science problems.

2. Fixed Offshore Installations

a. Introduction: Ice Mechanics. This section is concerned with ice mechanics as it relates to the engineering design of fixed offshore installations. The primary objective is to obtain detailed information on ice/structure interactions that will lead to the development and verification of models which relate large-scale deformations in ice fields to loads on structures. Because of the timing for satellite launch, it is highly unlikely that its data will be available in time to assist in the engineering design of first-generation offshore production structures in areas of current activity. Nevertheless, satellite radar data could be useful for providing information essential to the development of more reliable and cost-effective second-generation structures, assisting in the development of design criteria for the more difficult areas of the polar offshore (deep water sites of the Bering, Chukchi and Beaufort Seas, and the Antarctic), and conducting scientific and engineering studies of macroscale ice properties.

b. Problem Definition. The overall ice mechanics/fixed-structure problem can be divided into five major components, each of which has its subset of required information:

Table 2. Summary of Information Requirements for Ice Hazards and Features

Parameter	Measurement	Accuracy	Spatial Resolution	Temporal Resolution	Timeliness	Applicability of SAR	Alternative Systems
Pack-ice edge	Location, compactness	500 m	500 m	24 hours	24 hours	Yes	Scatterometry
Multiyear ice	Area %, floe size	10% 20 m	20 m	Weekly	3 days	Yes	Scatterometry
Very large pressure ridges	Height	2 m	10 m	Weekly	3 days	?	Laser profilometry, photography
Ice islands	Dimensions	20 m	20 m	Weekly	3 days	Yes	None
Icebergs	Dimensions	10 m	10 m	Weekly	3 days	Yes	None
Leads/thin ice	Location Width Orientation	1 km 20 m 10°	20 m	Semiweekly	24 hours	Yes	None

Properties of sea ice and their scaling. Here we are concerned with the material properties of sea ice (strength, stress-strain behavior, rupture criteria) and their dependence on the geometric scale of the interaction, the rate of loading, and the state of the ice. Ice state is, in turn, a function of several more basic parameters: brine volume (itself a function of temperature and salinity), ice grain size, and crystal orientation. The initial primary separation of ice types into the three classes of fresh water ice (lake or river ice), first-year ice, and multiyear ice would be very useful in that each of these types has characteristic salinity/brine volume profiles which give characteristic property profiles.

Geometry and bulk properties of ice features. In some ice-structure interaction problems the geometry and bulk properties of an ice feature are much more important than the properties of the individual ice blocks that compose the feature. Here we specifically refer to the properties of first-year ridges and rubble fields where information giving porosity, block size, degree of consolidation, and ice-ice cohesion or friction, are needed. Also of considerable interest are the geometric characteristics (length, width, height) and general areal distribution of the extreme (largest) values of features such as ridges, rubble fields, and ice islands. To obtain reasonable estimates of such extreme features, it will be necessary to determine the geometry of a large number of each type of ice entity.

Ice/structure interaction. Calculation of ice loads on a structure depends on a good understanding of the local ice failure processes near the structure. These processes, in turn, depend on: (1) characteristics of the structure and its mechanical response (diameter, geometry, surface characteristics, structural deflections, (2) ice feature characteristics (ice feature geometry and ice types), (3) ice temperature, and (4) ice movement rates. Sequential observations of local ice deformation patterns, rubble heights, and block sizes of the failed material would clearly reveal a great deal about the nature of the interactions.

Environmental driving force. Large-scale ice dynamics models can provide estimates of the driving forces averaged over large distances in the far-field. Near the structure, these far-field forces are modified by the structure geometry and relative stiffness and by the nature and geometry of the nearby ice features and the shoreline. Observations on the geometry of the large-scale deformation around the structure, the variations in ice thickness, and the number and orientation of open and refrozen leads would be useful.

In some situations, sufficient force may not be available to cause the ice features next to a structure to fail. Instead, stress is relieved by the failure of a weaker feature in the ice pack. Under these circumstances, the magnitude of the environmental driving force can be very important.

Ice movement rates. Ice movement rates are of considerable importance because it is the peak velocity during a movement event that appears to be critical in determining the design loads at failure as well as the local impact loads.

c. <u>Information Requirements</u>. Table 3 provides a detailed list of requirements for the accuracy and the spatial and temporal resolutions of the parameters discussed above. The first figure gives the desired accuracy while the second gives the minimum acceptable accuracy. If the requirement for block size determinations with a spatial resolution of <1 m are neglected (such information can be obtained from surface observations), a spatial resolution of 10 to 20 m seems adequate. A temporal resolution on the order of 6 to 12 hours is desirable. This requirement is driven by the need to know movement rates averaged over as short a time span as possible (it is also known that significant movement events occur in a few hours). It should also be noted that because these data will be used to calibrate and verify analytical models for determining ice loads on structures, there is no requirement for real-time or near-real-time image processing. A 2- to 6-month turnaround time is adequate.

As is obvious from examining Table 3, there are a number of parameters of interest that would not be measurable by the use of SAR: ice surface temperatures, ridge or deformation height, and ice thickness. This information can, however, be obtained via the use of infrared techniques, laser profilometry, and surface- or helicopter-based pulsed radar (100 MHz) respectively. There are also parameters where the use of SAR is questionable (fabric, scale effects, depth of consolidation, block size, and stress buildup). One of the purposes of the experimental program, which follows, is to explore the possibility of using SAR to study these parameters.

d. <u>Mission Requirements</u>. Table 4 summarizes the SAR requirements that are, at present, believed to be useful in studies of the interaction of ice with fixed offshore installations. The proposed research on the application of SAR to the specification of other questionable parameters may further add to this list.

e. <u>Program</u>. The primary objectives of this program would be verification of the ability to identify ice features of engineering interest and investigations of the information regarding ice/structure interaction that can be obtained.

Specifically, the following might be carried out. At a site of engineering interest, such as a grounded rubble pile in the Chukchi Sea, an artificial gravel island in the Beaufort Sea or a rock pinnacle such as Fairway Rock or Hannes Island, a series of SAR flights should be made over a period of 2 to 3 weeks. During each flight, variations should be made in the look and depression angle. Also, if possible, data should be collected at several frequencies. At the same time, data should also be collected using stress and temperature sensors embedded in ice frozen to the "structure." Ice character observations should be made with the imagery in hand within 2 days of each overflight.

Specific items needed are:

(1) Ice Properties

Table 3. Information Requirements for Ice Mechanics Problems

Parameter	Measurement	Accuracy	Spatial Resolution	Temporal Resolution[a]	Applicability of SAR	Alternative Systems
A. Ice properties						
1. Ice type	Area %	5-10%	0.1-1 km	1-10 days	Yes	Scatterometer or passive μwave
2. Ice surface temperature	°C	1-3%	1-10 km	1-10 days	No	Infrared
3. Fabric	Microstructure	Crystal size orientation	0.1-1 km	1-10 days	?	Ground-based radar
4. Scale effect			10-50 km	1-10 days	?	Marine radar, photography
B. Geometry/bulk properties of extreme ice features						
1. Ridges						
a. Areal distribution	% ridging	10%	1-10 km	1-10 days	Yes	Photography
b. Height	m	0.5-1 m	5-50 m	1-10 days	No	Laser
c. Width	m	5-10 m	10-20 m	1-10 days	Yes	Photography
d. Length	m	10-100 m	10-100 m	1-10 days	Yes	Photography
e. Depth of consolidation	m	0.5-1 m	10-100 m	10-50 days	?	? Ground-based radar
2. Floes						
a. Type	Floe type	FY, MY, glacial	10-100 m	1-10 days	Yes	Photography, passive μwave
b. Size	m	10-100 m	10-100 m	1-10 days	Yes	Photography, passive μwave
c. Thickness	m	0.5-1 m	10-100 m	1-10 days	No	Ground-based radar
C. Ice/structure interaction						
1. Local deformation pattern	m	10 m	10 m	6-24 hours	Yes	Photography
2. Height of deformation	m	0.5-1 m	5-50 m	6-24 hours	No	Laser
3. Block size	m	0.5-1 m	0.5-1 m	6-24 hours	?	Photography
4. Stress buildup prior to deformation	Identify stress wave	10 m	10 m	6-24 hours	?	? Passive μwave
5. Scale effect		0.5-1 m	0.5-1 m	Overlap		
D. Environmental driving force						
1. Large-scale deformation pattern	m	0.1-1 km	0.1-1 km	6-24 hours	Yes	Photography
2. Average thickness	m	1-5 m	1-10 km	1-10 days	No	Ground-based radar
3. Leads					Yes	Photography
a. Percent	%	10%	10-100 km	6-24 hours	Yes	Photography
b. Pattern	Pattern	10-100 m	10-100 km	6-24 hours	Yes	Photography
E. Ice movement rate	Point velocity	1-10 km/day	0.1-1 km	6-24 hours		

[a] Assuming a timeliness of data of 2-6 months.

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Table 4. Radar Requirements for Engineering Ice Mechanics

System Parameter	Specification	
	Desirable	Minimum Acceptable
Spatial resolution	1-10 m	20 m
Temporal resolution (over a site)	6 hours and overlap	24 hours
Absolute position accuracy	0.25 km	1 km
Timeliness	2 months	6 months
Area of interest	2 × 2 km	--
Ice type identification	First-year, multiyear, glacial, rafted, new	First-year, multiyear, glacial
Feature identification	Ridges, rubble, floes, leads	Ridges, rubble, floes, leads

(a) Ice Type

Automatic analysis is required for SAR data in order to facilitate the rapid differentiation of ice types and features of engineering interest. Studies should also be undertaken that would allow the controlled verification of such procedures.

(b) Ice Temperature

Accurate determinations of ice surface temperatures are required for a variety of different ice types and snow conditions. Such obervations are particularly important in both the fall (freezing) and the spring (melting).

(c) Ice Fabric

Investigations are required on whether any indication of ice microstructure can be determined from SAR data (it can be determined by surface-pulsed radar).

(d) Scale Effect

Information should be acquired on the spatial and temporal distribution of geometric discontinuities and mechanical inhomogeneities in the ice cover (leads, cracks, etc.).

(e) Ice Consolidation

Studies should be undertaken to explore the possibility of using SAR data to determine the degree and depth of consolidation of ice features.

(2) Geometry/Bulk Properties of Extreme Ice Features

(a) Ridges

Verification is required of ridge percent, length, and width estimates obtained from SAR.

An investigation of ways of estimating ridge height (depth) from SAR data or other sensor (e.g., laser profilometer) is also called for.

Correlations of heights, frequencies, drift directions, and ridge types should be assembled from the historical record.

(b) Floes

Verification of floe size and type estimates is required.

(c) Ice-Structure Interaction

The determination of sequential changes in the deformation pattern around grounded ice features such as "Katies Floeberg" or around offshore islands should include estimates of ridge height and the general geometry of ridges and rubble.

The scale effect should be studied by attempting to identify the temporal sequences for the occurrence of different failure submechanisms so that a loading hierarchy can be determined. This would require taking frequent sequential images.

(3) Movement

It is necessary to verify changes (if any) in ice feature signatures with the passage of time so that features can be positively identified and tracked. Also needed is an accurate positioning system so that repeat images will have a nearly constant coordinate frame of reference for mapping ice cover dynamics.

3. Navigation

a. <u>Introduction: Special Problems</u>. Ice of any type presents its own particular problems depending on the type of vessel and the type of ice. These problems fall into three main categories: safety, increased operational costs (usually related to increased transit times and wear on equipment), and environmental concerns. All ships transiting ice could utilize information on the subjects listed in Table 5. In most cases useful information on these subjects is provided by SAR.

b. <u>Problem Definition</u>. The problem here is quite simple in principle: to develop methods for rapidly determining the items listed in Table 5 from SAR imagery and then to transmit these data or summaries prepared from the data rapidly to ship operators at sea. It would also be useful to carry out studies that would lead to techniques for the remote sensing of ice pressure, ice deterioration, and snow cover (thick snow covers result in greatly increased friction against the ship's hull resulting in significant loss of speed).

c. <u>Mission Requirements</u>. Table 6 summarizes the mission requirements for a SAR system useful to ship operators. The requisite turnaround time is very short, 3 hours. This is caused by the fact that ice conditions that affect ships (leads, ice pressure against the hull) change very rapidly. Therefore, it is desirable to update the ice information at

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Table 5. Information Requirements for Navigation

Parameter	Measurement	Accuracy	Spatial Resolution	Temporal Resolution	Timeliness	Applicability of SAR	Alternative Systems
Ice edge	Location	100 m	100 m	3-12 hours	1 day	Yes	
Ice type	Areal %	5%	25 m	Weekly	1 week	Yes	
Ice thickness	Thickness	1 m	20 m	Weekly	1 week	?	Surface radar
Ice concentration	Areal %	5%	500 m	3-12 hours	1 day	Yes	
Ridging	Height patterns	2 m	25 m	Daily	1 day	Yes	
Leads	Areal % patterns	10 m	20 m	3-12 hours	1 day	Yes	
Floe size	Size	20 m	20 m	Weekly	1 week	Yes	
Ice pressure	Convergence	Sign of pressure	10-km^2 area	3-12 hours	1 day	?	?
Motion	Velocity	10 cm/s	25 m	3-12 hours	1 day	Yes	
Deterioration	Melt ponds	5%	10 m	Weekly	1 week	?	Passive μwave
Icebergs	Size	20 m	100 m		1 day	Yes	
	Location	20 m	100 m				
Ice islands	Size Location	20 m 20 m	100 m 100 m		1 day	Yes	
Snow cover	Thickness Location	20 cm	10 m	Weekly	1 week	No	?

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Table 6. Radar Requirements in Marine Navigation

Item	Specification	
	Desirable	Minimum Acceptable
Resolution length	20 m	50 m
Positional accuracy	500 m	1500 m
Frequency of coverage	3 hours	12 hours
Spatial coverage	800 km	160 km
Timeliness	3 hours	Daily

quite frequent intervals. If this proves to be operationally impossible, daily SAR imagery would still be useful in that it would reveal the general structure of the pack and would aid the ship captain in selecting an easy route through the ice. Two additional requirements not listed in the table are that the imagery must be transmitted to the ship in near-real-time and that a certain amount of image analysis must be completed for transmission at the same time. Examples are the areal percentage of different ice types and of ridged ice that occur in different segments of the image.

d. Experimental Program. It is known from both Seasat SAR imagery and from aircraft-borne SAR imagery that useful information on most of the parameters listed in Table 6 can be obtained from proper analysis of the imagery. The purpose of an experimental program is to develop techniques for rapidly analyzing such imagery and transmitting both the imagery and the reduced data to the ship. An important additional effort would be the development of a program to train ship captains in the effective use of such imagery.

The rapid automatic analysis techniques could be developed by using Seasat SAR imagery as a test case. Ultimately aircraft SAR data should be used in a simulation of the utilization of satellite SAR data.

4. Offshore Activities

a. Introduction: Ice Monitoring for Petroleum Operations. Petroleum companies are increasing offshore operations in and on ice in the world's frontier regions. Exploratory drilling and production activities in northern Alaska and Canada require both a historical knowledge of the regional ice climatology and a real-time operations support function. This section discusses the latter problem of providing ice monitoring services in support of day-to-day operations. It should, however, be noted that the information required for day-to-day operations will ultimately serve to extend and improve the quality of the data on the local ice climatology.

b. Problem Definition. There are a wide variety of environmental observations which are either necessary and/or advantageous to organizations involved in offshore petroleum activities in regions where ice is a problem. A list of observations of interest will be given later. The specific observations may change from site to site. For instance, at a deep-water site in the Beaufort Sea, ice island tracking would be a critical parameter. In shallow water in the same region, ice islands could be ignored because of their deep draft. They could also be ignored in the Bering Sea, as they have not been observed to enter this region. In most cases, the regions we are concerned with are small (a few tens of kilometers) with their size being governed by the size of oil fields. However, it is necessary to monitor conditions over a wider region so that advance warning can be given if certain hazardous situations start to develop. Within each region, the greatest interest is focused on a few spots such as the sites of gravel islands, drill ships, gravity structures or other locations of concentrated offshore operations.

The problem is, in principle, simple--obtain detailed observations at very short time intervals, process the imagery, and then extract the information of interest in near-real-time, and transmit either the extracted information or the imagery or both to the affected remote site. In practice, this will undoubtedly be difficult to accomplish. However, a significant effort toward the development of a real-time analysis and data distribution system will pay dividends not only in petroleum activities but in all aspects of SAR utilization.

c. Information Requirements. Table 7 gives a listing of environmental observations that are of interest to offshore oil and gas operators. Some of these observations only apply to specific regions. For instance, ice islands are a problem in the Arctic Ocean and its exits, icebergs are only encountered in the eastern Arctic, and multiyear ice does not occur in the Bering Sea. There are a large number of different parameters that are of interest. SAR contributes useful information on the great majority of these. At the bottom of the table we have also listed several parameters that are desired as complementary observations for the data obtained from SAR.

d. Mission Requirements. Table 7 gives a list of requirement estimates for a SAR system useful to organizations involved in offshore petroleum activities. Particularly interesting here is the question of the repetition frequency of observations. This, of course, depends on the specific uses of the data. For most offshore activities there are needs for data at several different levels: large-scale "strategic" lower-frequency observations that provide the "big picture"; smaller scale, more-frequent "tactical" observations; and detailed continuous closeup observations. The requirements at these different levels are spelled out in Section III. We believe that the detailed, continuous "close-tactical" observations are not at present particularly suitable to satellite techniques and will therefore be satisfied by the use of "fixed" remote sensing systems that are mounted on ships or offshore platforms. Even so, "tactical" observations will require repetition frequencies of 1 day or less and turnaround times of 3 hours or less. If these rather stringent requirements cannot be met, SAR will lose much of its attractiveness to the operational community.

e. Program. The principal effort required will be in developing efficient ways for analyzing SAR imagery and transmitting the resulting analysis to the user in the field. Time should also be devoted to training people in the petroleum industry in the interpretation of SAR imagery. Existing SAR data could be used in such an exercise or, preferably, new data could be collected at a site where offshore activities are currently underway. The general area north of the Mackenzie Delta would be an excellent first choice for such a location.

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Table 7. Information Requirements for Offshore Petroleum Activities

Parameter	Measurement	Accuracy	Spatial Resolution	Temporal Resolution	Timeliness	Applicability of SAR
Ice edge	Location	1 km	1 km	3-12 hours	3-12 hours	Yes
Ice concentration	Areal %	5%	10 m	3-12 hours	↓	Yes
Thickness	Thickness	1 m	20 m	Weekly	↓	?
Ice type	Areal %	5%	25 m	Weekly	↓	Yes
Floe size	Diameter	10 m	20 m	Weekly	↓	Yes
Ridge height	Height	2 m	10 m	Weekly	↓	No
Ridge and rubble geometry	Areal % Geometric pattern	5%	20 m	12 hours	↓	Yes
Leads	Areal % Geometric pattern	2%	25 m	3-12 hours	↓	Yes
Ice islands	Size Location	25 m 1 km	25 m	Daily	↓	Yes
Ice movement	Geographic location	1 km	1 km	Daily	↓	Yes
Ice pressure	?	?	10 km	3-12 hours	↓	?
Icebergs	Size Location	200 m	10 m 1 km	3-12 hours	↓	Yes
Wind speed		1 m/s	100 × 100 km	3-12 hours	<3 hours	No
Wind direction		20°		3-12 hours	↓	No
Wave height		1 m	50 × 50 km	3-12 hours	↓	No
Wave period		5 s	50 × 50 km	3-12 hours	↓	Yes
Barometric pressure	Millibars	1 mbar	100 × 100 km	3-12 hours	↓	?
Sea-surface temperature	Radiometer	2° C	100 × 100 km	Daily	↓	No

III. ICE INFORMATION AND MISSION REQUIREMENTS

This section summarizes the ice information requirements needed for science and for operations in ice-laden waters. In some of the following tables, to avoid confusion with the term "resolution" which is an instrument parameter, a new term "minimum detection required" is introduced to refer to the minimum detectable height, width, extent, and separation (MDH, MDW, MDE, and MDS) necessary for information on the feature of interest to be useful. The resolution dimension will generally be smaller than the minimum detectable value in order to enable the adequate identification of an extended target.

A. SCIENCE REQUIREMENTS

The requirements for the science programs are summarized in Table 8. As can be seen, the climatological research programs are in many ways the least demanding, in that they can tolerate repeat times of up to 30 days and require a less highly resolved view of the state of the ice. However, climatological studies invariably require global coverage. The other extreme is given by programs that study the material response of sea ice. As sea ice can change rapidly, frequent and highly focused observations are required to adequately delineate these changes. One important difference in the three science areas is the desired turnaround times in processing the imagery. As climatology is by nature retrospective, processing time of up to 6 months could be tolerated. Material response, on the other hand, is commonly concerned with rapid changes requiring turnaround times of, at most, a few hours if imagery is to be made available in a timely fashion to investigators involved in field observations. Circulation studies are usually undertaken in a manner similar to climatological investigations and therefore do not commonly require near-real-time data. The exception to this would be periods when field observations were underway along an ice edge and it was necessary to use imagery in making rapid adjustments in field sampling procedures to accommodate changes in ice conditions.

B. OPERATIONS STUDIES REQUIREMENTS

As the requirements for sea-ice operations are appreciably more demanding than are the requirements for sea-ice science, they will be presented in somewhat more detail. Tables 9 through 20 give measurement requirements for ice features, and Table 21 gives complementary data set requirements for research problems in sea-ice operations.

1. Offshore Activities

Table 9 shows measurement requirements for offshore activities in sea-ice-covered oceans. Typically, this work is primarily concerned with locating and estimating the magnitudes of hazards caused by the presence of large ridges and large multiyear ice floes. Table 10 summarizes mission requirements for these requirements.

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Table 8. Ice Science Information Requirements

Field	Parameter	Resolution	Repetition, days	Horizontal Scale (Swath), km	Accuracy
Circulation	Ice velocity	5-30 km	1-3	100	100 m/day
	Ice type	10 km	10-30	100	20%
	Ridge density	30 km	10-30	100	20%
	Lead area	100 km	1-3	100	0.2% (total)
	Ice extent	30 km	1-3	1000	10 km
	Air temperature	2 K	3	1000	2 K
	Wind speed	1-2 m/s	3	1000	1 m/s
Climatology	Ice velocity	300-100 km	3-10	100-200	200 m/day
	Ice type	50 km	10-30	Global	10%
	Ridge density	30 km	10-30	100	20%
	Lead area	200-500 km	3-10	Global	0.2% (total)
	Ice extent	50 km	10-30	1000	100 km
	Air temperature	3-5 K	3-10	Global	3 K
	Wind speed	2 m/s	3-10	Global	2 m/s
Material response	Ice velocity	1 km	1-3	100	50 m/day
	Ice type	300 m	3	10	10%
	Ridge density	1 km	1-3	10	10%
	Lead area	1 km	1-3	10	0.1% (total)
	Ice extent	300 m	1-3	10	300 m
	Air temperature	3 K	1	500	2 K
	Wind speed	1 m/s	1	500	1 m/s

Table 9. Ice Conditions of Relevance for Offshore Activities

Ice Parameter	Requirement
Ice type identification (Multiyear, first-year, thin ice, open water)	MDE = 100-300 m
Floe size	MDE = 100 m
Concentration by type	MDE = 100-300 m, accuracy 5-10%
Thickness	Operation-dependent, generally inferred from type
Ridges	MDH = 1 m, MDS = 10 m
Rubble fields	MDE = 100 m, discriminate ridges within rubble
Multiyear hummock fields	MDE = 100 m, MDH = 2 m
Ice islands	MDE = 100 m
Leads	MDW = 5-10 m
Motion	Position ±1 km

Table 10. Offshore Mission Requirements

Function	Strategic[a]	Tactical[b]	Close-tactical[c]
Repetition frequency	2-4 days	1 day or as required	Continuous
Positional accuracy	5-10 km	2-5 km	50 m
Area covered	300 × 800 km	100 × 100 km	700 km^2
Turnaround time (from acquisition to end user)	6-12 hours	<3 hours	Instantaneous

[a]Distance from site >50 km
[b]Distance from site <50 km
[c]Distance from site <15 km

2. General Navigation

All ships operating in or near sea ice require certain basic information which includes ice-edge parameters, ice extent, concentration and type, icebergs, ice thickness, and surface features (e.g., ridging, hummocks), and locations of icebergs.

It must be recognized that these ice observation needs will vary as a function of the activity, ship type, season, and vessel location. For the purposes of designing a radar satellite, it is necessary to consider the navigational requirements for conventional ice-breakers, for ice-breaking oil tankers, and for ice-breaking tankers carrying liquified natural gas (LNG). Table 11 presents measurement requirements for general ice-breaker navigation, and Table 12 shows the consequent mission requirements. Navigation concerns have two time scales, the tactical, or less than 24 hours, and the strategic or greater than 24 hours.

3. Tanker Navigation

Because tankers operating in ice-frequented areas are assigned specific routes (Figure 2), their requirements differ from the ones for general navigation. Table 13 shows tanker navigation information requirements. Table 14 shows information requirements for LNG operations, and Table 15 shows mission requirements for general ice-breaking tanker operations.

4. Ice-Engineering Requirements

Ice-engineering research is again a retrospective activity such that data are not usually needed until 2-6 months after acquisition. In a few cases, investigation will need near-real-time data to update field sampling schemes. Table 16 shows measurement requirements for ice-mechanics research, and Table 17 shows the appropriate mission requirements.

5. Ice-Forecasting Requirements

Table 18 gives the parameters needed for short-term ice forecasting for both site-specific (small scale) and regional scale predictions. The forecasting services should provide forecasts for a time frame of less than 24 hours; short term (1-3 days); medium-term (15 days); long term (30 days); and seasonal (3-4 months).

C. SUMMARY OF REQUIREMENTS

The specific ice information requirements are listed in Table 19. The table combines all operational requirements. The range of minimum detectable parameters represents the range of observables for both strategic and tactical requirements. Table 20 lists the consequent overall mission requirements for research on operational problems.

In addition, the requirements for complementary data from other platforms, notably data buoys, are given in Table 21.

Table 11. Information for General Navigation

Ice Parameter	Priority[a] Strategic[b]	Priority[a] Tactical[c]	Remarks
Edge	1	1	
Type	1	1	
Thickness	1	1	
Concentration	1	1	
Ridging	1	1	Frequency, orientation, height
Rafting	3	3	
Hummocking	2	1	Extent
Leads	2	1	Orientation
Floes	2	1	Size and type
Deterioration	3	3	Thaw holes, puddling
Pressure	1	1	
Motion	2	1	
Icebergs	3	1	Size and type
Ice islands	3	1	
Snow cover	3	1	Thickness

[a]Scale of priority 1-3: 1 = high, 2 = medium, 3 = low.

[b]Strategic information needs are related to operations on greater than a 24-hour period.

[c]Tactical information needs are related to operations on less than a 24-hour time scale.

Table 12. General Navigation Mission Requirements

Data Characteristics	Strategic	Tactical
Timeliness of availability	6-12 hours	2-3 hours
Positional accuracy	1500 m	500 m
Resolution length (minimal)	500 m	Icebergs, 5 m All others, 50 m
Frequency of coverage	1-3 days	12-24 hours
Spatial coverage	800-1600 km	160 km

Table 13. Tanker Navigation Ice Information Requirements (includes Beaufort)

Parameter	Requirement
Ice type	
(Multilayer, first-year, thin, open water)	10%
Concentration	2%
Flow size	100 m
Ridges:	
Height	1 m
Spacing	300 m
Icebergs[a]	5-20 m
Leads:	
Extend	50
Separation	500 m
Ice island fragments	20 m
Surface condition	Snow or melt-ponded

[a]It is desirable to be able to detect clusters of small bergs down to growler size.

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Table 14. LNG Tanker Ice Information and Mission Requirements

Ice Parameter[b]	Frequency of Coverage[a]				Requirements				Notes
	Area I		Area II		Geographical Accuracy		Accuracy of Measurement		
	Des, h	Min, h	Des, h	Min, h	Des, km	Min, km	Des	Min	
Ice thickness (first-year)	24	168	24	168	2	5	20 cm	50 cm	The detection of multiyear ice as such is sufficient.
Ridging									
Vertical height	6	24	24	96	2	5	1 m	2 m	Minimum detectable sail height of 1 m.
Density	6	24	24	96	2	5	10%	20%	Distinguish between two ridges 20 m apart.
Orientation	6	24	24	96	2	5	10°	20°	
Ice Pressure	6	24	24	96	2	5	10%	?	Detect positive or negative pressure, provide data to estimate whether magnitude is sufficient to create ridges/leads.
Ice concentration	6	24	24	96	2	5	10%	20%	
Ice type	6	24	24	96	2	5	N/A	N/A	
Leads, polynyas									
Orientation	6	24	24	96	2	5	10°	20°	
Area	6	24	24	96	2	5	10%	50%	Minimum detectable lead width of 50 m.
Surface characteristics	6	24	24	96	2	5	10 m	20 m	Minimum detectable surface feature 10-m^2 area.
Icebergs	6	24	24	24	2	5	5 m	20 m	Minimum detectable iceberg, 8000 m^3 (approximately 20 m on a side).
Ice edge or boundary	6	24	24	96		5	2 km	1 km	

[a]Des = desirable.
Min = minimum acceptable.
[b]In decreasing importance.

Table 15. General Tanker Mission Requirements

Ice Parameter	Frequency		Spatial Extent[a]	
	Strategic	Tactical	Strategic[b]	Tactical
Icebergs	2 days	1/2 day or as required	500 × 5000 km	150 × 500 km
Sea ice	3 days	1 day or as required[c]	300 × 3000 km	150 × 900 km

[a]Accuracy: Strategic = 10 km; Tactical = 5 km.
[b]This coverage may be obtained from successive passes.
[c]In certain areas and times of year this may be 1/2 day.

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Table 16. Information Requirements for Ice Mechanics Research

Parameter	Measurement	Accuracy	Spatial Resolution	Temporal Resolution[a]
A. Ice Properties				
1. Ice type	Area %	5–10%	0.1–1 km	1–10 days
2. Ice surface temperature	°C	1–3%	1–10 km	1–10 days
3. Fabric	Microstructure	Crystal size orientation, conglomerate	0.1–1 km	1–10 days
4. Scale effect				
B. Geometry/bulk properties of extreme ice features				
1. Ridges				
a. Areal distribution	% ridging	10%	1–10 km	1–10 days
b. Height	m	0.5–1 m	10–100 m	1–10 days
c. Width	m	10–20 m	10–20 m	1–10 days
d. Length	m	10–100m	10–100 m	1–10 days
e. Depth of consolidation	m	0.5–1 m	10–100 m	10–50 days
2. Floes				
a. Type	Floe type	FY, MY, glacial	10–100 m	1–10 days
b. Size	m	10–100 m	10–100 m	1–10 days
c. Thickness	m	0.5–1 m	10–100 m	1–10 days
C. Ice/structure interaction				
1. Local deformation pattern	m	10 m	10 m	6–24 hours
2. Height of deformation	m	0.5–1 m	10–100 m	6–24 hours
3. Block size	m	0.5–1 m	0.5–1 m	6–24 hours
4. Stress buildup prior to deformation	Identify stress wave	10 m	10 m	6–24 hours
5. Scale effect		0.5–1 m	0.5–1m	Overlap
D. Environmental driving force				
1. Large-scale deformation pattern	m	0.1–1 km	0.1–1 km	6–24 hours
2. Average thickness	m	1–5 m	1–10 km	1–10 days
3. Leads				
a. %	%	10%	10–100 km	6–24 hours
b. Pattern	Pattern	10–100 m	10–100 km	6–24 hours
E. Ice movement rate	Point velocity	1–10 km/day	0.1–1 km	6–24 hours

[a] For assumed timeliness of 2–6 months.

Table 17. Mission Requirements for Engineering Ice Mechanics

Item	Specification	
	Desirable	Minimum Acceptable
Spatial resolution MDW	1-10 m	20 m
Temporal resolution (over a site)	6 hours and overlap	24 hours
Absolute position accuracy	0.25 km/pass	1 km/pass
Timeliness	2 months	6 months
Area of interest	2 x 2 km	-
Ice type identification	First-year, multiyear, glacial, rafted, new	First-year, multiyear, glacial
Feature identification	Ridges, rubble, floes, leads	Ridges, rubble, floes, leads

Table 18. Requirements for Small Scale to Regional Scale Forecasts

Parameter	Accuracy[a]	Resolution[a]	
		Spatial	Temporal
Drift	50 m/day (1 km/day)	1 km (5 km)	6 hours (5 days)
Concentration	2% (10%)	10 km (25 km)	1 day (3 days)
Thickness	20 cm (1 m)	25 km (50 km)	1 day (3 days)
Edge	0.5 km (3 km)	1 km (10 km)	1 day (3 days)
Ridging			
Density (No./km)	10% (50%)	50 m (100 m)	1 week (4 weeks)
Orientation	10° (30°)	-	1 week (4 weeks)
Height	1 m (5 m)	-	1 week (4 weeks)
Lead			
Orientation	10° (30°)	-	1 day (3 days)
Area	10% (50%)	50 m (100 m)	1 day (3 days)
Type (fractional area)	5% (10%)	1 km (25 km)	1 week (4 weeks)

[a]Small scale (regional scale).

Table 19. Summary of Ice Information Requirements

Parameter	Description	Range of Minimum Detectable Observation		Function
		Smallest	Largest	
Sea-ice type	Multiyear, first-year, thin ice, open water	MDE 100 m	MDE 1 km	Identification
Floe size	Multiyear, first-year	MDE 10 m	MDE 100 m	Isolated floe
Concentration	Multiyear, first-year	MDE 100 m	MDE 300 m	Aerial
Ridges	Multiyear, first-year	MDH 0.5 m MDW 10 m MDL 10 m MDS 10 m	MDE 1 m 20 m 100 m 500 m	Height Width Length Separation
Leads	Open water, thin ice	MDW 5m MDE 10 m MDS 500 m 10°	MDW 10 m MDE 100 m MDS – 20°	Width Extent Separation Orientation
Rubble fields	First-year	MDE 100 m	MDE –	
Hummock fields	Multiyear	MDE 100 m MDH 2 m	– –	Extent Height
Icebergs Ice islands	Fresh-water ice	MDE 5 m MDE 20 m	MDE 20 m MDE 100 m	Size Size
Motion	Point velocity	1 km/day	10 km/day	Ice movement
Thickness	Multiyear, first-year	0.2 m	0.5 m	
Ice pressure	Multiyear, first-year	–	–	Divergence/convergence
Snow	On all ice types	–	–	Pressure, wet/dry

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Table 20. Summary of Ice Mission Requirements

Function	Strategic		Tactical		Close-Tactical (Site-Specific)
	Minimum	Maximum	Minimum	Maximum	
Frequency of coverage	1 day	4 days	12 or as required		Continuous
Spatial coverage	300 x 800 km	300 x 3000 km	100 x 100 km	150 x 900 km	∿700 km^2
Positional accuracy	1.5 km	10 km	500 m-5 km		∿50 m
Timeliness	6 hours	12 hours	2 ms	3 hours	Instantaneous
Geographical coverage	76° N	85° N	76° N	78° N	--

Table 21. Complementary Data Sets

Parameter	Accuracy
Wind speed	2 m/s
Wind direction	20°
Wave height	1 m
Wave period	5 s
Barometric pressure	0.1 mb
Sea surface temperature	0.1 K
Ice surface temperature	1 K
Currents	0.5 cm/s

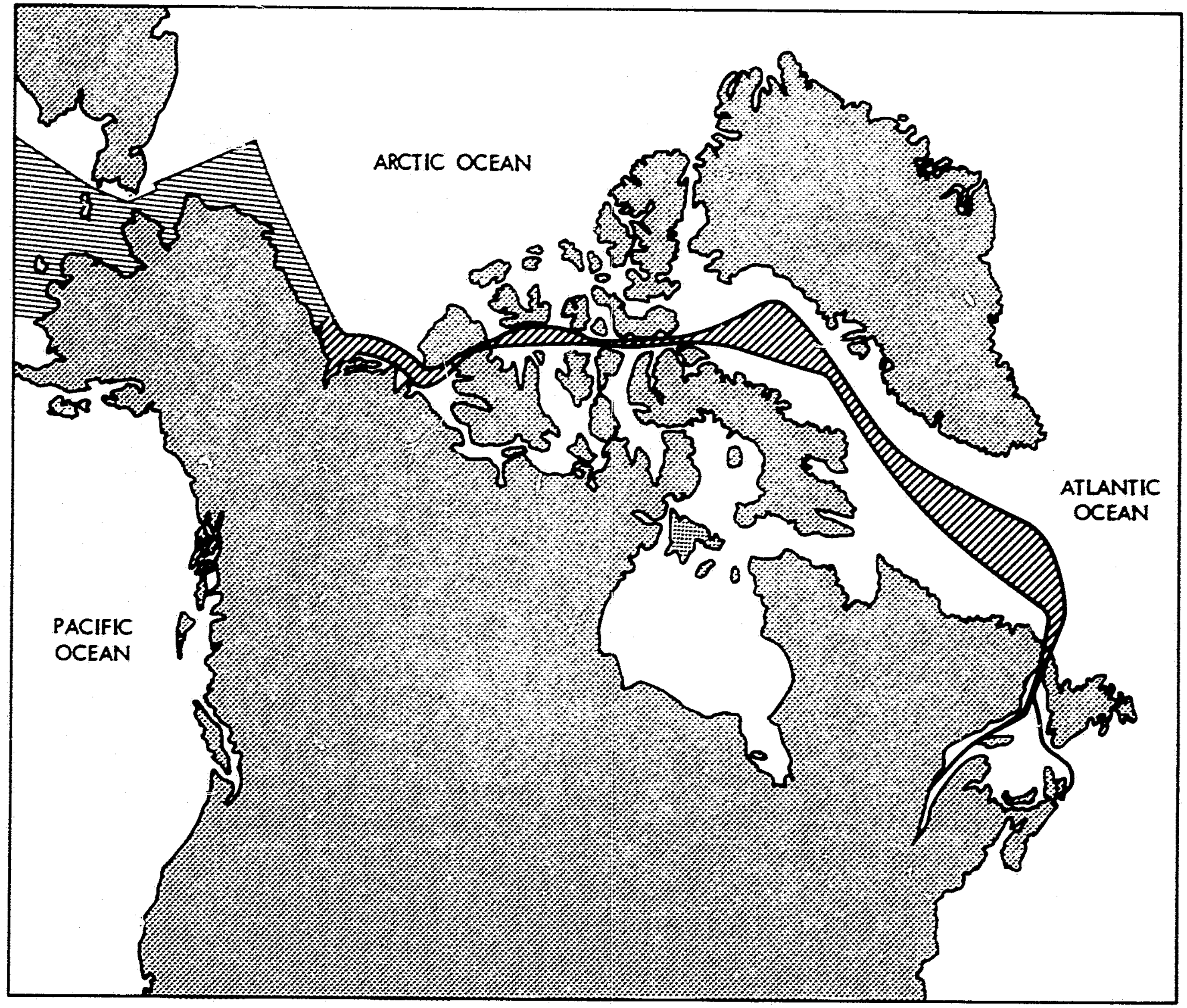

Figure 2. Hatched area shows the Arctic Ocean and marginal seas in which oil- and gas-bearing tanker operation is now contemplated. Exploration discoveries could alter the figure in the Canadian Archipelago.

IV. MISSION SYSTEM COMPONENTS

Information on specified time and space scales is needed to enable progress on the sea-ice operations and science problems discussed in Section II. To acquire this information in usable form and timely fashion, an integrated program is called for. While the central element of the system is the space-borne SAR, the remainder of the system is also significant, and its design surely affects total cost and level of scientific success. The system is seen to have the following seven interrelated components.

A. SATELLITE INSTRUMENTATION SYSTEM

It is recommended that a satellite designed to provide basic ice data carry a SAR and complementary scatterometer or radiometer plus a buoy interrogation system with the appropriate communications links, ground stations, and data-processing facilities. While the actual data products required by different users do not vary greatly, there are significant differences in timeliness requirements, such that data system scaling is determined by the total number of near-real-time, or short-turnaround, data products described in Section III. The fundamental data products from the instrumentation system are acquired as 2-dimensional arrays, or images, of ice type, concentration, movement, and deformation. The final recommended instrument array which will be discussed in Section V has considerable flexibility without loss of usefulness.

B. DATA DISSEMINATION SYSTEM

All users will require eventual access to data, and some will have unique highly-demanding needs. In particular, two user groups need high-quality, short-turnaround information--the groups doing operational simulations and <u>in situ</u> research. In both cases, operators/investigators in the field will be required to make critical decisions based on program-supplied information. This calls for satellite communication links sufficient to carry the required data within the specified times. Other users will have more relaxed data needs that can be accommodated by low-data-rate systems or mailed tapes.

C. DATA BUOY SYSTEM

The satellite sensor data must be augmented by appropriate <u>in situ</u> meteorological and oceanographic data. Considerable experience, beginning with the AIDJEX 1972 experiment, supports the use of satellite-monitored buoys to provide data on position, atmospheric pressure, and other variables such as air and water temperature. Such a buoy-satellite system is clearly needed for the present program. For greatest efficiency, the buoy communication system should utilize the satellite communications link. Thus, electronic systems for buoy interrogation should be included in the instrumentation. Also, the program should review and improve buoy technology to optimize it for sea-ice research.

D. AIRCRAFT/SHIP/FIXED INSTALLATION DATA SUPPLEMENT

Satellite instrument and buoy data are applicable to all the problems recommended for attack. In addition to the satellite and buoy data, many problem areas require ancillary data from other sources such as high-resolution airborne radar, ship radar, fixed-installation radar on drill rigs or promontories, and weather station reports. Some of this data will be transmitted through the satellite communications system. In general, these data are not a program problem in terms of acquisition, but their transmission may be required to ensure project success.

E. ICE MICROWAVE PROPERTIES

The microwave radiance and backscatter data acquired by the satellite instruments is converted into ice-type information by algorithms using the microwave characteristics of specific ice samples. Information concerning the physical properties of different ice types is primarily developed from <u>in situ</u> measurements and secondarily from the study of satellite data records. At present, considerable information on the microwave characteristics of ice has been acquired. Nevertheless, an adequate base of regional seasonal data sets does not exist. In particular, the effects on microwaves of snow and surface liquid water--both as a skin of water and as slush--are poorly known. Also, some frequency bands have received little attention. The project should undertake to acquire any missing surface conformation data by making <u>in situ</u> or, at worst, aircraft measurements. This effort will take several years and may in fact generate as many questions as it answers. For example, it is known that Arctic multiyear ice has a spatially varying emissivity, but the cause of the differences is not known.

F. OPERATIONAL PROCESS SIMULATION

This program is designed to facilitate in the transition of SAR from a research tool to a sea-ice operational tool. Thus, a detailed scenario is required for each of several operational simulations involving navigation and offshore activities such as drill-ship operations. In general, these simulations require descriptions of ice conditions at the observation time as well as forecasts of future ice conditions (see Section III). The models which will perform these forecasts must be developed in coordination with the program office and they must be on-line at launch, having been given trial runs on Seasat or aircraft data. The experience gained from these simulations will be used to refine the algorithms and communications system.

G. SEA-ICE RESEARCH

The sea-ice science and operations research problems discussed in Section II will all employ satellite and buoy data and ice microwave properties information. Many of the research problems require improved understanding of air-sea-ice interaction mechanisms requiring, in some cases, surface programs involving ships and aircraft. For the most part, useful

results come from using sensor and buoy data in numerical models. Some of these models are essentially completed and in place; others barely exist as conceptions. The work of establishing these models could take 2-5 years. This effort should be long-term; it cannot be created at launch and be expected to function effectively.

V. RADAR PARAMETERS

At present, gaps still exist in the knowledge of the incidence angle dependence of the radar backscatter coefficient over the frequency spectrum of interest for defining an optimum radar for sea-ice observation. Part of this gap has now recently been filled based on the preliminary results of the AES RADARSAT Experiment carried out at Mould Bay, NWT during October 1981. A full discussion of the frequency and incidence angle, a dependence of backscatter, calls for review of the earlier work and a consideration of the preliminary conclusions of recent work.

The important ice types, as discussed in Section III, fall mainly into three categories, namely, multiyear ice (MY), first-year ice (FY), thin ice (TI), and a category for open water. Figures 3 and 4b show 13.3-GHz radar backscatter data for a wide variety of ice types and conditions found in the Arctic winter (Gray et al., 1981). The lowest return is from calm water and the next lowest originates from smooth first-year ice under winter conditions. At this frequency, MY ice can be readily discriminated from FY and TI for incidence angles greater than 20. The difference in σ_0 between FY and TI ice is highly variable and depends very much on the thickness of TI ice. The radar backscatter for TI can vary about 15 dB as the ice thickness increases from less than 5 cm to 15 cm. This backscatter change is almost as large as the dynamic range found for all ice types. The phenomenon is however easily explained--the increase in radar backscatter associated with the increase of ice thickness is due to the formation of frost flowers (a rough surface ice grown from briny water found in and on the surface of thin ice). The effect of wind on the backscatter from water going from a wind speed of 2 m/s to 20 m/s is also shown (Jones et al., 1978). This effect causes some problems in interpretation of σ_0 at the marginal ice zone, in polynyas, and in large leads. Depending on wind speed and incidence angle, the radar backscatter of open water can equal that of any ice type. At incidence angles above 30^{o}, the multiyear ice/open water discrimination is assured even at winds of 20 m/s.

During the early melt season (Figure 4a), MY, FY, and very likely TI, cannot be distinguished because of the presence of wet snow on the surface. At time of freeze-up, TI can easily be distinguished from FY and MY ice as shown in Figure 5. The FY ice which has survived one summer, to become second-year (SY) ice on 1 October and MY ice, which has survived two or more summers, are indistinguishable based on microwave behavior.

Figure 6 depicts the radar backscatter for different ice types and conditions at a frequency of 1.5 GHz (Figure 6a) and 5.2 GHz (Figure 6b). Figure 6a shows the ability to discriminate between thick FY (TFY) ice, MY ice, and pressure ridges (PR) during winter conditions. TY and MY ice were not found to be distinguishable between 10 and 60^{o} (Onstott et al., 1979). Figure 6b, on the other hand, was obtained at a frequency of 5.2 GHz during the month of October 1981 at Mould Bay, NWT (RADARSAT Ice Group, private communication). Due to unusually warm weather, both the FY and MY ice had wet surfaces and the ice temperatures were near the melting point. Consequently, one would not expect to be able to discriminate FY ice from MY ice based on the earlier discussion of Figure 4a. On the other hand, the ice in Figure 6

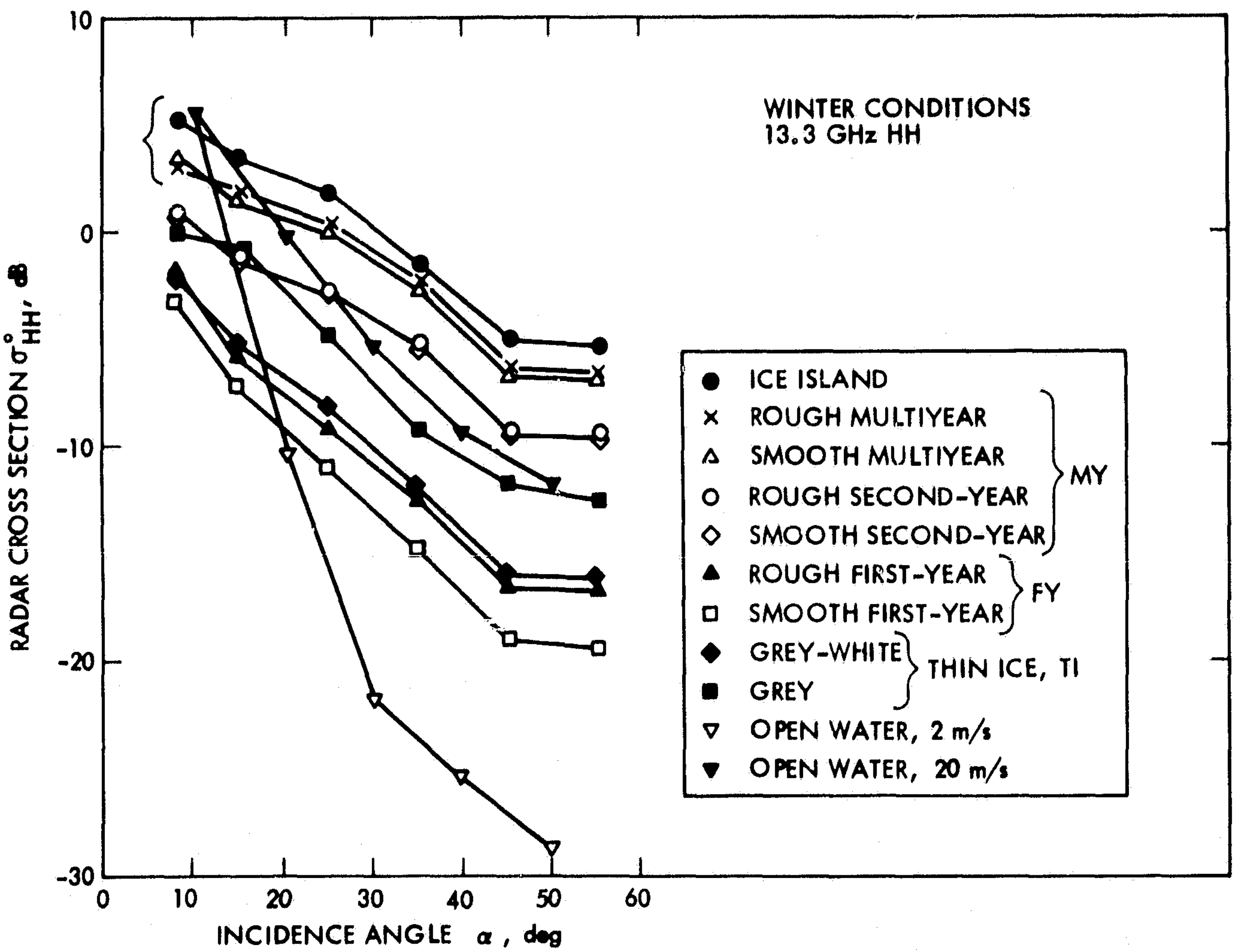

Figure 3. Ice backscatter results at 13.3 GHz for ice types found in the Beaufort Sea (Gray et al., 1981) and for open water with 2 and 20 m/s winds (Jones et al., 1978). At this high frequency there is considerable difference in backscatter value for the different ice species.

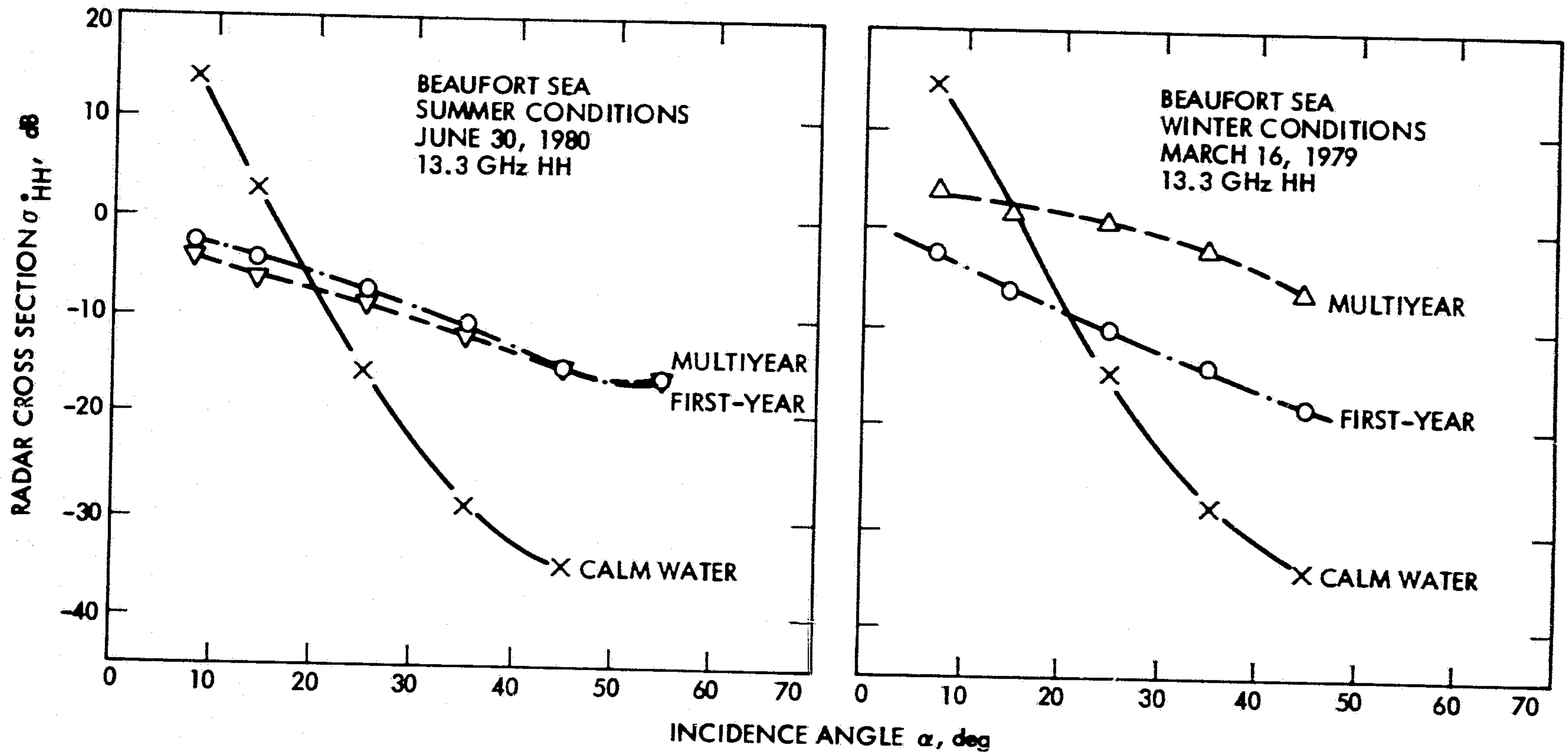

Figure 4. Ice backscatter results at 13.3 GHz for ice in the Beaufort Sea in winter and in the melt season when the surface is composed of melt ponds, wet snow, and wet ice. In summer at this wavelength, there is effectively no ice type contrast.

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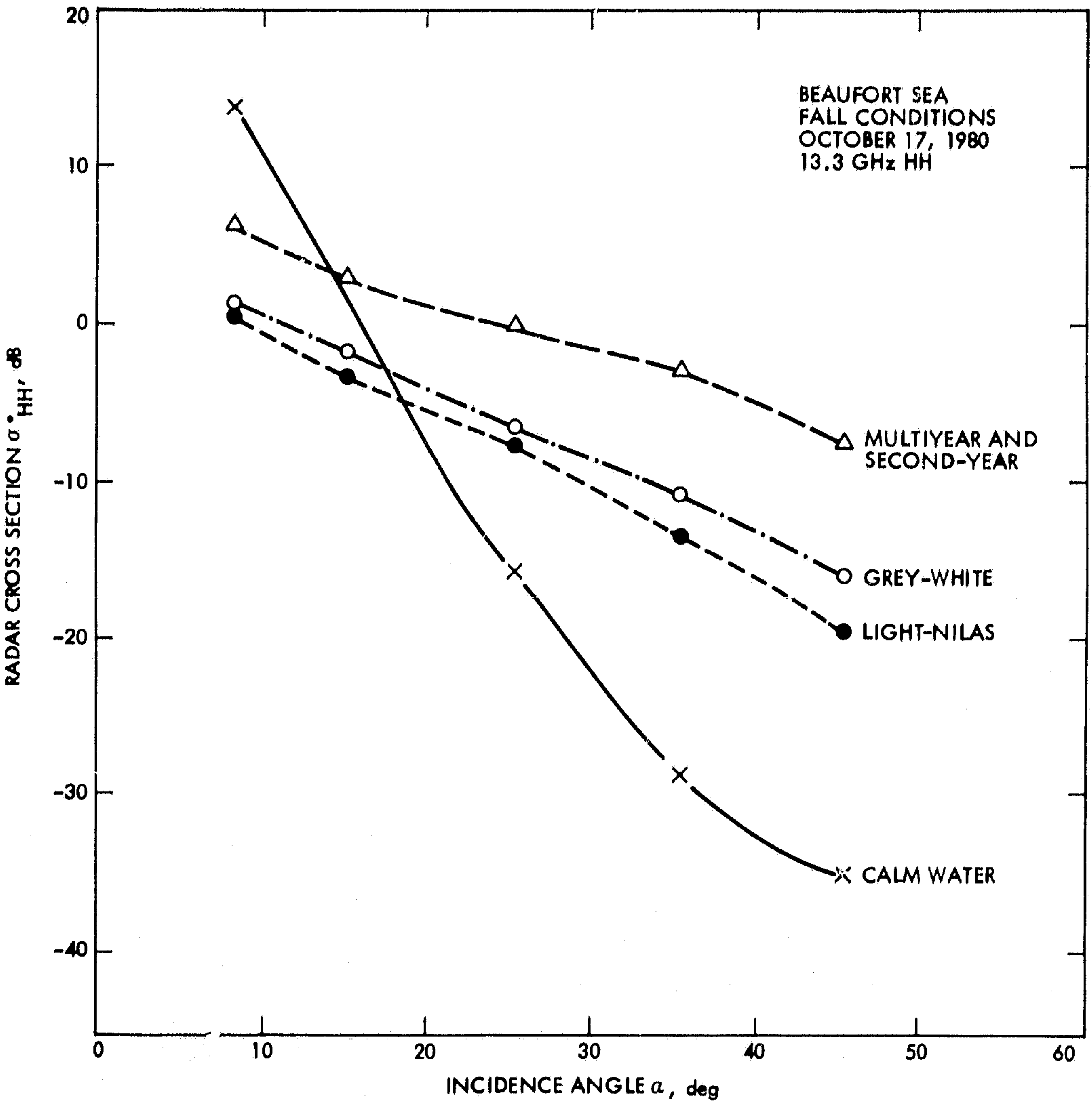

Figure 5. Ice backscatter results for the early fall freeze-up at 13.3 GHz showing the difference in incidence angle behavior between multiyear ice and the thinnest ice types where light-nilas is a slushy layer and grey-white ice is 10-30 cm thick.

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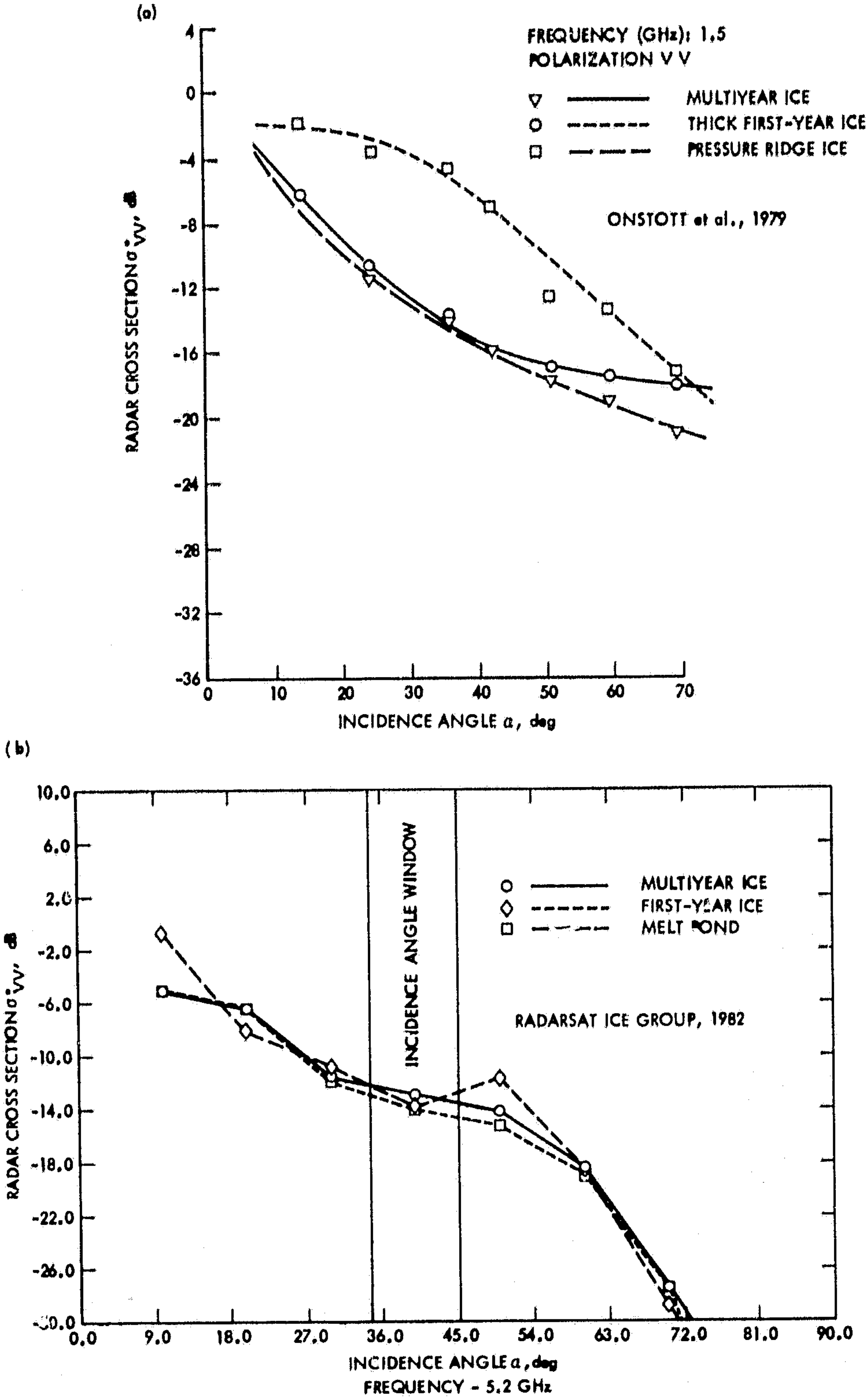

Figure 6. Lower-frequency ice backscatter results. In (a) spring results are shown for 1.5 GHz, near the Seasat SAR frequency, and in (b) 5.2 GHz results are shown. In both cases the principal ice types are not distinguishable in the microwave.

does not have a surface cover of wet snow comparable to that of Figure 3a; thus, this result may indicate no difference in microwave backscatter at this frequency. Figure 7, from data taken simultaneously with that of Figure 6, further supports this viewpoint in that it shows that at 13.3 GHz these wet MY and FY ice samples are distinguishable as was the case in Figure 3.

In Figures 6b and 7, a new ice type has been introduced in the form of frozen melt ponds (MP). These features form an integral part of a MY ice floe and have different physical properties than the other components of MY ice. Conclusions about the behavior of MP has to await a proper analysis of the data.

Figure 7 depicts the frequency dependence of the Mould Bay data set for three ice types. The data were taken during the earlier part of October when the ice was close to the melting point. Figure 7a gives the results for a radar backscatter incidence angle of 30° and Figure 7b for 40°. The basic form of the curves does not change appreciably from 30° to 40° at the lower frequencies. A significant change in backscatter behavior occurs at X-band (near 11 GHz) where a jump of about 14 dB for MY and 9.6 dB for FY ice takes place. On the average, the difference in backscatter between FY and MY for a frequency of less than 10.5 GHz is about 2.5 dB and above 11.5 GHz about 5.4 dB. As a comparison, one data point at 10.4 GHz based on the NORSEX data set for MY ice has also been included in Figure 7 (Maetzler et al., 1981). The agreement as evidenced for both incidence angles at 30° and 40° is remarkable. The conditions at NORSEX and Mould Bay were very similar.

The backscatter change with frequency does not occur smoothly as was speculated before this new data set became available. What this data does show is that at the lower end of the frequency spectrum (1-10 GHz) all frequencies do a poor job of discriminating between FY and MY ice. It is only at frequencies greater than 11.5 GHz that discrimination between MY and FY ice becomes reliable, based on radar backscatter alone. The change in backscatter behavior near 11 GHz is probably due to the change from roughness scattering at lower frequencies to roughness plus structural scattering at higher frequencies.

It is interesting to compare the emissivity as a function of ice type using data at C-band from the NIMBUS-7 scanning multifrequency microwave radiometer (SMMR). Aproximately calibrated results taken in February 1979 are given in Figure 8 for MY, FY, and water. The trend in emissivity difference for MY and FY ice is the same as for σ_0--it decreases with decreasing frequency. The differences in C-band emissivity are so small that discrimination is very unlikely. Another very revealing data set (Figure 9) shows emissivity variations as a function of frequency for very thin ice (pancake) and MY ice taken at the end of September and beginning of October 1978 (Maetzler et al., 1981). In this situation, useful ice-type discrimination at low frequencies is clearly not feasible.

The key elements in the resolution and swath width determination came from the feature tracking requirement. Very high resolution is unnecessary because of the nature of ice features as being "bright" and having spatial scale rarely below 5-10 m so that a 25-m resolution adequately locates the

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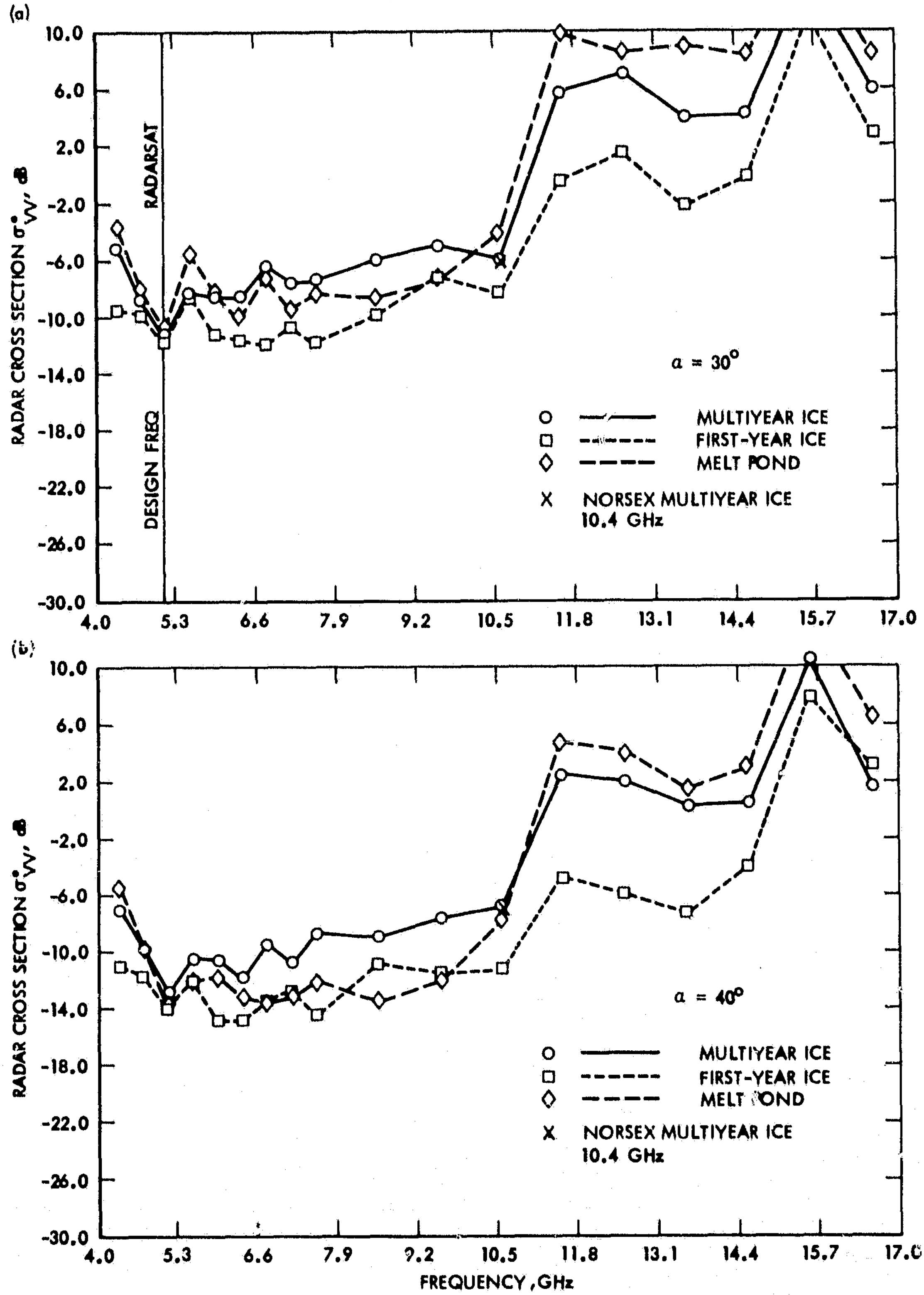

Figure 7. Frequency dependence of the backscatter coefficient for two incidence angles, 30° and 40°, from recent RADARSAT results. The change in backscatter differences at 10-11 GHz is significant for ice-type determination. Data points from NORSEX in Fram Strait are also shown.

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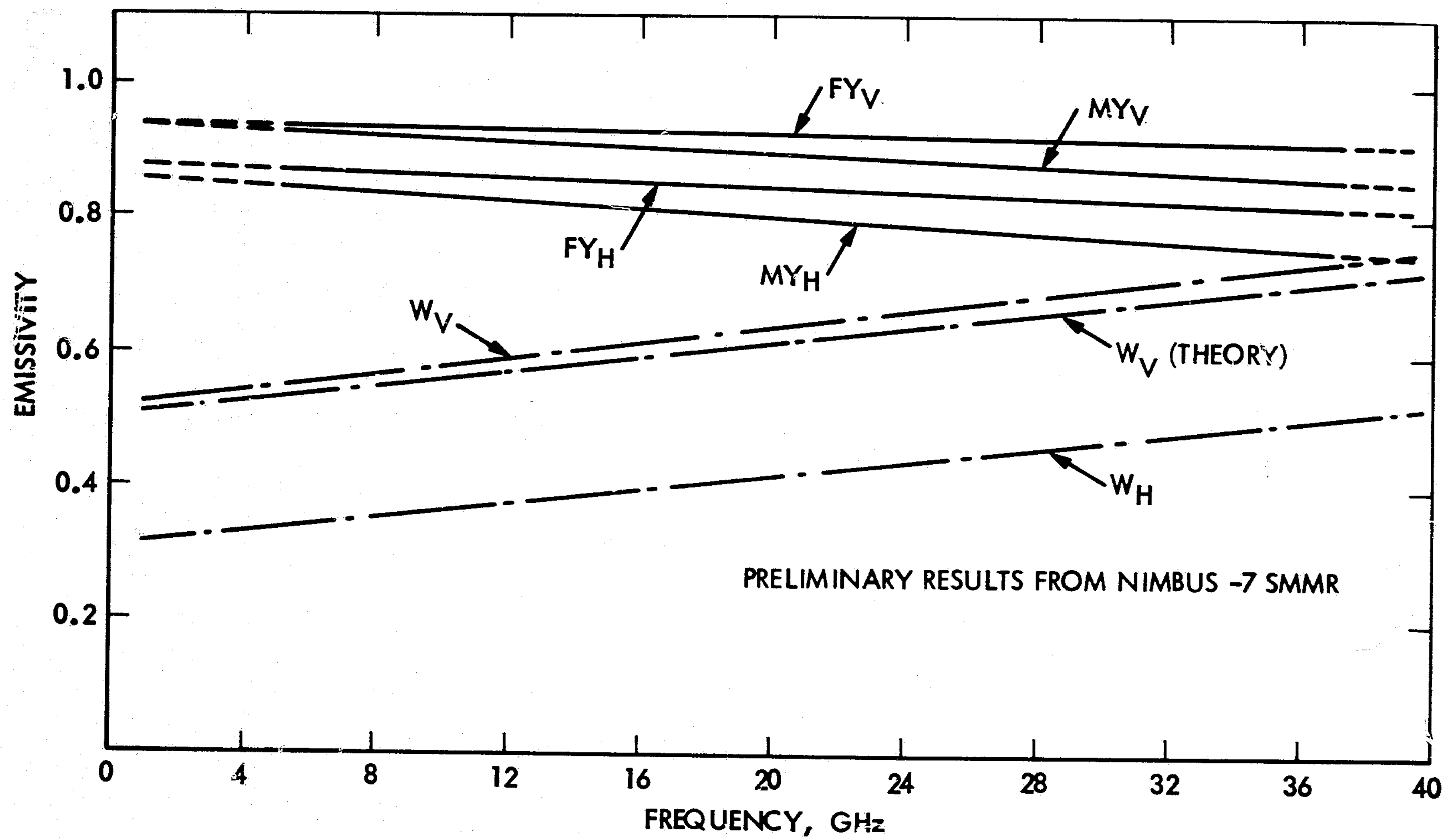

Figure 8. Ice emissivity values as a function of frequency. Results for water (W_H and W_V), first year ice (FY_V and FY_H) and multiyear ice (MY_V and MY_H) are shown for both polarizations at a 50° incidence angle.

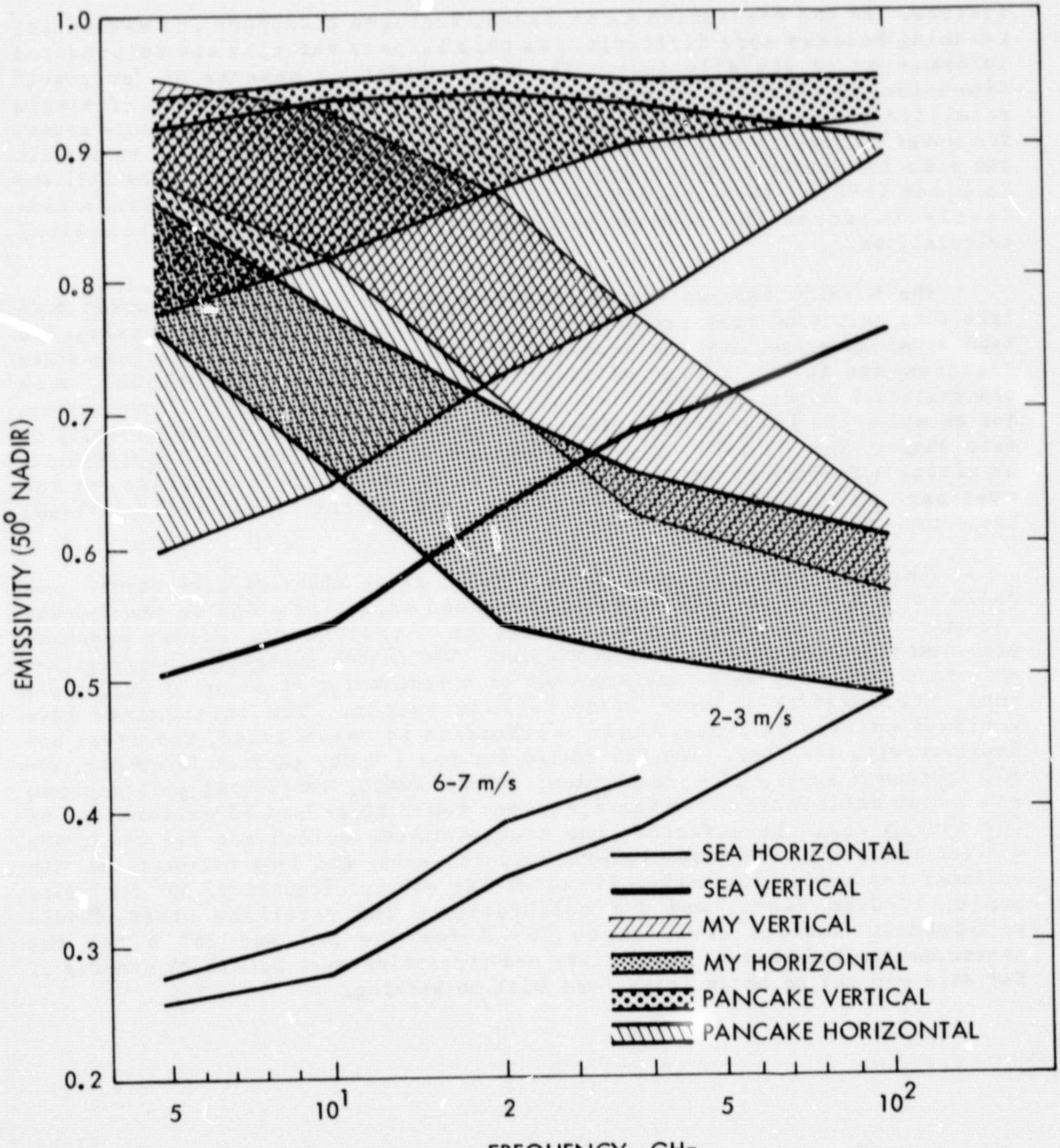

Figure 9. Sea-ice emissivity data taken during NORSEX in Fram Strait. Pancake ice, a close-packed array of ice disks a few centimeters thick, is the formation mechanism for first-year ice in large open areas under certain wind conditions. Clearly, low-frequency data are not useful for ice-type discrimination.

feature. As the resolution is degraded, features disappear and sequential tracking becomes more difficult. As this happens velocity and deformation information is steadily lost. The swath width, a measure of "snapshot" dimension, is likewise controlled by the velocity determination. A single satellite can produce repeat coverage on 1-3 day intervals. In some areas, ice moves so rapidly that a region of 100-km dimension is too small to contain the same ice features on the 3-day-repeat interval, as was learned by Hall and Rothrock (1981). Thus a swath of 200 km is called for. Such a swath also vastly improves the system sampling capability for climatological calculations.

The mission information requirements can be approximately broken down into three kinds of measurements: ice feature identification and tracking, ice type areal coverage, and environmental variables. Table 22 summarizes these requirements in the format of instrument parameters. In Table 22, some observational requirements do not clearly belong to one category or another. For example, the ice type of a given floe can be determined radiometrically or from shape. Thus it is a variable which can be obtained for some applications as either a feature or an areal total. The choice of method depends for the most part on horizontal scale--a global examination cannot rely on visual inspection of every floe.

There are two approaches to satisfying these observational needs. One calls for a SAR in the 11-15 GHz band and one calls for a SAR in the 1-2 GHz band (L-band) augmented by a scatterometer or radiometer. Either approach also needs <u>in situ</u> data buoy augmentation. The latter instrument aggregate--an L-band SAR, a KU-band scatterometer or a radiometer at 19 or 37 GHz, and a buoy interrogation sensor--is an optimum system. The instruments have verified success in space, their calibration is established, and users are familiar with the data. The SAR called for has 1-2 GHz carrier frequency, 20-50^{o} incidence angle, 25-m resolution, 200-km swath, horizontal polarization, and 1-2 dB calibration. The SAR frequency could be raised if calibration of the system could be assured. The scatterometer called for has 11-15 GHz carrier frequency, 10-km resolution, 1000-km swath, and 1-dB calibration. The optional radiometer has either 19- or 37-GHz carrier frequency, 50^{o} incidence angle, 1000-km swath, and 2 K calibration. The satellite orbit should accommodate surface coverage to 76^{o} N for the SAR and 86^{o} N for the scatterometer/radiometer. Data links and processing must permit 35 minutes of SAR data per day to be in image form with no backlog.

Table 22. Summary Instrument Parameters

Instrument Parameter	Requirement From Feature	Requirement From Ice Type Areal Cover Scatterometer (Radiometer)	Requirement From Environment Variable
Carrier Frequency	1-2 GHz	11-15 GHz (19 or 37 GHz)	N/A
Resolution	25 m	1-50 km (20-50) km	100-500 km
Incidence angle	20-50°	20-50° (50%)	N/A
Swath	100-200 km	800-1500 km	N/A
Repetition	1-3 days	3-10 days	1/2 day
Orbit (swath center ground track)	76-88°	84-86°	N/A
Calibration	±1 dB relative ±2 dB absolute	±1 dB absolute (±2 K)	±1-2 m/s ±2 K

VI. THE APPROACH TO AN OPERATIONAL SAR

The Seasat SAR and an assortment of aircraft SAR flights have clearly proven the operational and research potential of SAR as a tool for ice surveillance. For the problems of greatest interest and significance, the value of application of a space-borne SAR is not an issue, in spite of the fact that much more data acquisition and analysis are needed for different regions and seasons, and in spite of the fact that ice models utilizing SAR-derived variables as driving terms have not as yet been developed.

Since SAR is well accepted as the key observational tool for ice surveillance, the steps required in making the transition to an operational SAR should also receive consideration. At present, an information system with SAR data products as a key component has not been assembled. Clearly, such a system must be studied, simulated and demonstrated before operational SAR can be visualized as a complete system. System requirements at every step, including data quality, parameter accuracy, observer capability, throughput time and information channels, must be determined.

Thus, in the context of moving toward an operational SAR, the recommended program performs two jobs: it assists in filling out the SAR sea-ice parameter-value table by adding information on seasonal and regional variations, and it provides a data set for use in the development and demonstration of an operational system. These tasks are neither small, nor trivial. To construct an operational system without the satellite effort is not really an option. On the one hand, aircraft data substitution is expensive. On the other, trying to second-guess the thoughts of an ice-breaking tanker pilot surrounded by 10-m-thick ice floes is folly.

This program has been developed as a tool for attacking science and operational problems involving sea ice. In the progression toward operational SAR, the issue of dual science/operational success arises. In effect, does the design of a satellite and information system for operational simulation in some way compromise the research data set? The answer is clearly no. As in almost every measurement issue, the operational need is for a more stringent interpretation capability, higher resolution, and faster data processing. A system constructed for sea-ice operational research and simulation will provide a science data set of uncompromised usefulness and quality.

A long-range schedule for development of operational SAR clearly involves prelaunch projects such as examination of existing data sets, further investigations on microwave properties of sea-ice types, studies of time and space scales of critical phenomena, and the development of models employing satellite-acquired data. Postlaunch activities are of two sorts. One is evaluating ice feature retrieval success; the other is the use of SAR-derived ice information to simulate and demonstrate operational applications using models developed before launch. Thus, the value addition of the SAR data applied to operational problems can be established within a reasonable time, perhaps two winter seasons, after satellite operation begins, if proper prelaunch development is performed. At that time SAR should be fully demonstrated as an operational tool for sea-ice application.

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VIII. GLOSSARY

FIREX	Free-Flying Imaging Radar Experiment (U.S. NASA).
First-year Ice	Ice which is in its first freezing season and has not survived a summer melt.
Floe	A piece of pack ice 10 m to 10 km across which moves as a rigid body.
Glacier	A mass of snow and ice continuously moving to lower ground or into the sea.
Growler	A fragment of floating glacier ice up to 3 m in diameter.
Iceberg	A floating piece of glacier ice, usually carved from an ice tongue or shelf.
Ice Shelf	The terminus of a glacier as partially or mostly floating ice which is usually laterally confined.
Ice Tongue	The terminus of a glacier as grounded ice in the sea.
Lead	A long narrow opening in the ice pack.
Lomonosov Ridge	A submarine ridge of about 2000 m in depth running approximately from Greenland nearly across the pole and on to Siberia.
Multiyear Ice	Ice which has survived at least one summer melt (strictly, more than two summers--for present use, the distinction between second-year and multiyear is of no value).
Nilas	Thin new ice formed from sintering of the millimeter fragments of ice called frazil.
Polynya	An opening in the ice pack which is inherently 2-dimensional and of at least large floe dimension.

RADARSAT	A proposed radar satellite (Canada DEMR/AES).
Ridge	Pile-ups of deformed ice from compression and shearing of ice floes.
SAR	Synthetic Aperture Radar, an imaging system.
Scatterometer	A calibrated scanning radar.
Sea Ice	Ice found at sea which has originated from the freezing of sea water.
Timeliness	Time elapsed between aquisition of raw data and transmittal of image-form information to user.

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